Economics of Damage Controlled Seismic Design

by

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Abstract

The economic impacts of Loma Prieta and Northridge Earthquakes have shown that there is an urgent need for a change in earthquake resistant design philosophy. This thesis explores the economic advantages of damage controlled seismic design and suggests this design methodology as the new design strategy for the new generation of codes. An application of damage controlled seismic design is also given as an example.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

Acknowledgment

First of all, I would like to thank Professor Jerome J. Connor, my advisor, for his encouragement and guidance.

I don't even want to try to thank my family, especially my parents, because I can't thank them enough.

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Ani, Hamra, and Ozlem, thank you for being with me through everything.

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Chapter 1

Introduction

1.1 Motivation

An earthquake can have a great impact on a nation's economy. Earthquakes result in significant damage, both structural and nonstructural (Fig. 1.1). They also injure people and disrupt transportation. They are one of nature's greatest hazards to life. They occur suddenly and interrupt the usual flow of life.

During a major earthquake, a large amount of kinetic energy is input to the building. The building should be capable of absorbing and dissipating this energy in a nondegrading manner over many cycles of substantial deformation. The manner in which this energy is transformed in the structure determines the level of damage. All codes imply that to design a building which would respond to a severe seismic action elastically is technically possible, but very expensive.

The codes of practice for seismic regulations provide limitations for the integrity of the structure and life safety during large infrequent earthquakes. The design criteria in most building codes are based on the philosophy of designing the structure to resist moderate earthquakes without significant damage and to resist major earthquakes without structural collapse. For example, it is especially articulated that the purpose of the earthquake design provisions of Uniform Building Code 97 (UBC97) is to prevent major structural failures and loss of life, not to reduce damage. The maximum interstory drift allowed in UBC97 [16] is 0.025 times the story height for structures having a fundamental period of less than 0.7 second and 0.020 times the story height for structures having a fundamental period of 0.7 second or greater. According to many researchers, the architectural damage due to an interstory drift angle of 0.02 is essentially 100%. Considering that the architectural cost is about 25% of overall cost, and the structural cost is 27% [11], a design based on UBC97 would result in a significant economic penalty.

Figure 1.1: May Company Parking, Whittier Narrows, California Earthquake [27]

In conventional design, it is accepted that demand will exceed the elastic capacity and inelastic action will occur under extreme loading. The structural elements which experience inelastic action are detailed for ductility, which is the ability of a structural system to undergo large inelastic deformation without collapsing. Structural failure is prevented at the expense of significant structural and nonstructural damage, which can result in repair costs that may be as significant as the cost associated with the collapse of the structure.

This leads to the conclusion that in order to design an economically feasible structure, damage should be controlled. Damage controlled design is a design approach where the performance (level of damage) of a structure for a given earthquake is specified and the design is performed accordingly. Applying the damage controlled design method to a structural system allows the structure to be used after a strong earthquake with reasonable repair cost. The goal is to minimize earthquake-related overall cost to the building owner. Economic considerations include not only costs related to the damage repair but also costs resulting from business interruption. By controlling the damage, the overall cost of the structure is also under control. The motivation is to reduce the economic impact of an earthquake.

Damage to structural components of a building can be controlled if displacements can be limited to predetermined values for a specified level of the earthquake shaking. In this thesis, we search for the allowable value of the damage.

1.2 Thesis Outline

The focus of this work is on damage controlled design. It advocates that it is the most rational design approach if one considers the economic consequences of earthquakes.

Chapter 2 deals with the conventional design method, i.e. ductile design, its application requirements and its shortcomings. Certain aspects of the Uniform Building Code 97 design requirements for reinforced concrete structures are presented, and the drawbacks of the code's approach are discussed.

To achieve damage control, modern seismic design tools are needed. The application of some existing tools is discussed in Chapter 3.

To be able to apply the damage controlled design method, the concept and the procedure should be clearly understood. Chapter 4 explains the concept and discusses different approaches for estimating damage.

Finally, in Chapter 5, some example designs are analyzed and evaluated with respect to the degree of damage control that they exhibit.

Chapter 2

Conventional Seismic Design

2.1 Special Moment Resisting Frame

According to existing earthquake codes, buildings are designed to resist minor low intensity earthquakes that occur several times during its lifetime without any damage, i.e. all structural components should remain in the elastic range. They should also resist moderate earthquakes, that are excepted to occur once during the lifetime, without structural damage. Both structural and nonstructural damage is allowed for a high intensity earthquake with a return period much longer than the design life, but the structure cannot collapse. Structural damage refers to the damage of the load carrying members. Nonstructural damage refers to the damage of nonstructural elements of the building, such as architectural facades, partition walls, and ceilings.

Since the elastic limit of the structure is allowed to be exceeded during a severe seismic action, the structure has to be able to undergo inelastic deformation without losing a large percentage of its strength. This structural property is called ductility.The conventional seismic design method relies on the ductility capacity of the structural members for achieving its aim.

To design a building that would respond to a severe seismic action elastically is technically possible, but expensive. That is the reason why the codes suggest inelastic response, i.e. ductile design.

Ductile members, by experiencing large inelastic deformation, can absorb a substantial amount of the earthquake induced kinetic energy. However, they may experience a significant amount of structural and nonstructural damage which may result in the structure being non-repairable.

To achieve the required ductility, frames are detailed such that a beam sway mechanism (Fig. 2.1a) develops rather than a column sway mechanism (Fig. 2.1b).

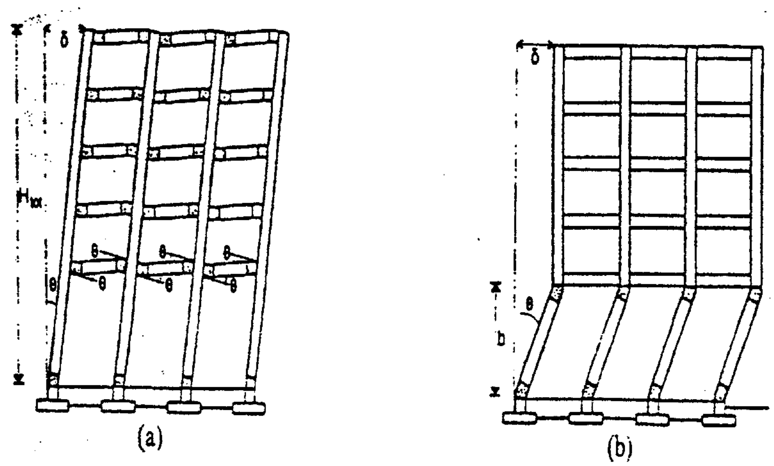

Figure 2.1: a)Beam Sway Mechanism b)Column Sway Mechanism

In a building structure, the beams, which are relatively easy to repair, are not crucial elements to structural stability. Therefore, it is logical to design the building such that during an earthquake the inelastic deformation is expected to occur in beams, and the more important elements, such as columns, respond elastically. This objective is achieved by requiring the sum of the flexural strength of the columns at each beam-column joint to exceed by some margin the sum of the combined beam flexural strength, which is called strong column-weak beam approach. In this way, the majority of plastic hinges will be located in the beams, at so called 'critical regions'. In the strong column-weak beam approach, the beams are intentionally designed weaker than columns, i.e. beams are forced to yield earlier. A consequence is that, in most buildings, a strong column-weak beam frame results in much larger column sizes than that which would be expected for withstanding only the gravity loads. The interstory drifts required to achieve significant hysteretic energy dissipation in critical regions are generally large and usually result in substantial damage to nonstructural elements such as infill walls, partitions, and ceilings.

Seismic codes take advantage of ductile yielding by reducing the level of seismic design force, typically to a level four to six times lower than the strength required for the structure to remain elastic [3]. In this way the demand will exceed the elastic capacity and inelastic action will occur.

Although the current seismic approach is based on strong column-weak beam concept, the likelihood of the formation of plastic hinges in columns, which requires confinement of concrete columns by transverse reinforcement, should also be considered. Confinement of concrete by properly designed and detailed reinforcement improves strength and deformability of the core, and in this way the overall behavior of a concrete column is also improved.

The behavior of longitudinal reinforcement in columns effects the deformability of confined concrete beyond the peak stress. Spalling of the cover at approximately the peak stress makes the longitudinal reinforcement susceptible to buckling, so sufficiently high lateral reinforcement should be provided for the stability of longitudinal reinforcement. The amount of lateral reinforcement plays an important role on post-peak characteristics of confined concrete.

2.2 Seismic Design Requirements for Reinforced Concrete Structures of Uniform Building Code 1997

The purpose of the seismic design provisions of Uniform Building Code 1997 (UBC 97) is to minimize life safety hazards, and to avoid catastrophic failures of structures. To achieve this goal, the code makes use of the ability of carefully detailed concrete components to dissipate a significant amount of earthquake induced energy through hysteresis, and allows damage such as: cracking, crushing of concrete, and yielding of steel.

According to UBC 97 [16], the story drift for the maximum inelastic response shall not exceed 0.025 times the story height for structures having a fundamental period of less than 0.7 second, and 0.020 times the story height for structures with a fundamental period of 0.7 second or greater. In some exceptional cases, where it can be demonstrated that a greater drift can be tolerated by both structural and nonstructural elements without affecting life safety, these drift limits can be exceeded.

The strong column-weak beam approach requires the flexural strengths of the columns to satisfy the following constraint

$$\sum M_e \geq \frac{6}{5}\sum M_g \tag{2.1}$$

where

ΣM_e - sum of moments, at the center of the joint, corresponding to the design flexural strengths of the columns framing into that joint.

ΣM_g - sum of the moments, at the center of the joint, corresponding to the design flexural strengths of the girders framing into that joint.

To ensure ductility, the requirements for beams are:

-The width-to-depth ratio shall not be less than 0.3

-The width shall be greater than 254 mm, but not more than the width of the supporting member.

-The area of the tension steel must satisfy

$$A_s < 1.38 \times \frac{b_w d}{f_y} \tag{2.2}$$

$$\rho > 0.025 \tag{2.3}$$

where

A_s- area of tension reinforcement

b_w - web width

d - effective depth of section

f_y - specific yield strength of reinforcement

ρ – tensile reinforcement ratio

- The maximum spacing between the hoops shall not exceed any of the following requirements: one quarter of the effective depth; eight times the diameter of the smallest longitudinal bar; 24 times the diameter of the hoop bars; and 305 mm.

The seismic design requirements for columns are:

- The ratio of the total reinforcement area to the cross-sectional area of the column shall not be less than 0.01 and shall not exceed 0.06.

- The amount of spiral reinforcement must satisfy

$$\rho_s > 0.12 \times \frac{f_c}{f_{yh}} \tag{2.4}$$

$$\rho_s > 0.45 \times \left(\frac{A_g}{A_c} - 1\right) \times \frac{f_c}{f_y} \tag{2.5}$$

where

ρ_s - ratio of volume of spiral reinforcement to the core volume confined by the spiral reinforcement

f_c - specified compressive strength of concrete

f_{yh}- specified yield strength of transverse reinforcement

A_g - gross area of section

A_c - area of the core of spirally reinforced member

f_y - specified yield strength of spiral reinforcement

- Transverse reinforcement shall be spaced at distances not exceeding one quarter minimum member distance and 102 mm.

2.3 Shortcomings

The ductile design approach, which allows inelastic response, can result in permanent damage and a repair cost that may be comparable to the total loss of the structure. In order to control damage, the displacements need to be limited to predetermined values which are based on an expected level of seismic action.

Economic losses also include business interruption. A number of buildings survived the Loma Prieta Earthquake of 1989 with little structural damage and no loss of life, but since there was extensive nonstructural damage (Fig. 2.2), they had to be evacuated. Consequently, a large number of people had no place to work, and the companies suffered monetary losses [26].

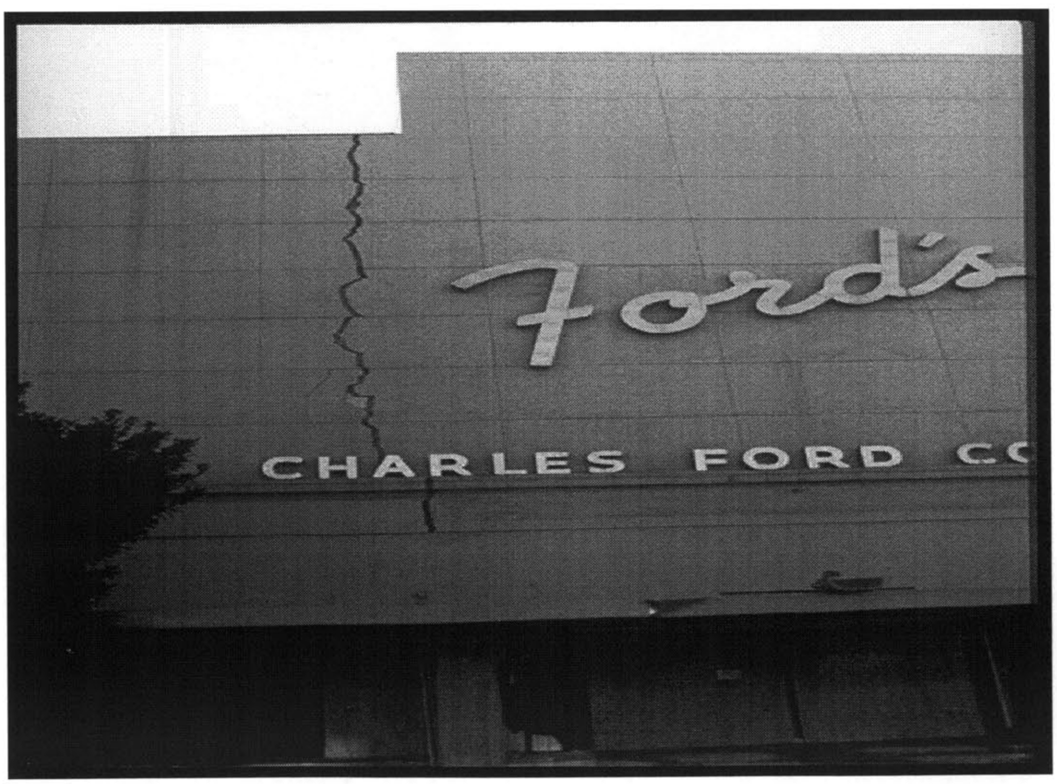

Figure 2.2: Cracks in Department Store Facade, Loma Prieta, California Earthquake [21]

The Northridge Earthquake of 1994 resulted in at least $20 billion of damage, but caused the loss of only 57 lives [4]. The Loma Prieta Earthquake resulted in $8 billion of damage and a low number of deaths [19]. This data substantiates the UBC goal of ensuring live safety. However, the economic losses can not be ignored, and the issue of whether seismic design should change from life safety only to damage control and functionality needs to be seriously considered. Preservation of life as a sole objective is not enough. Improved design methods are needed to minimize the cost of recovery.

Furthermore, there are certain types of structures such as hospitals, police stations, communication buildings for which damage is unacceptable since they must remain operational after a severe earthquake. As a consequence of the Loma Prieta earthquake in San Francisco and Oakland, the 911 system, which allows one to dial 911 on a phone to report an emergency and request urgent assistance, failed and did not function for several days because the response of the building which houses the switch gear and computers damaged the equipment [26]. This type of loss of function must be avoided.

Chapter 3

Various Modern Seismic Design Tools

3.1 Supplemental Passive Damping Devices

As a response to the shortcomings associated with the conventional seismic design, a number of innovative approaches have been proposed. Adding supplemental passive damping devices is one of them.

During a seismic event, the input energy is transformed into both kinetic and strain energy. The effect of damping is to decrease the level of the strain energy, which results in less story drifts during a seismic event. Energy dissipation devices reduce the energy absorption in the frame and limit the forces that the earthquake can induce in the structure. They confine the hysteretic behavior to specially designed and detailed regions of the structure. In this way, inelastic behavior in gravity load resisting structural elements is avoided.

One of the first cross-braced concrete frames with seismic energy dissipation devices in the bracings was built in Wanganui, New Zealand in 1980 [3]. The building obtained its lateral load resistance from diagonally braced precast concrete cladding panels. The precast concrete braces had round mild-steel tube inserts at one end, which were designed to yield in tension and compression. Each of these steel inserts consisted of a sleeve housing a specially fabricated steel tube 90 mm. diameter and 1.4 m. long. A movement gap was provided through the surrounding structure, and buckling was prevented by the surrounding sleeve and concrete. [8]

The damping devices that are mostly in use are viscous fluid dampers, viscoelastic dampers, friction dampers, and added damping and stiffness devices (hysteretic damper) (Fig. 3.1). The energy dissipation characteristics of the damping devices may not be ideally viscous, but they can be related with different levels of accuracy to an equivalent damping coefficient, which may be amplitude and frequency dependent.

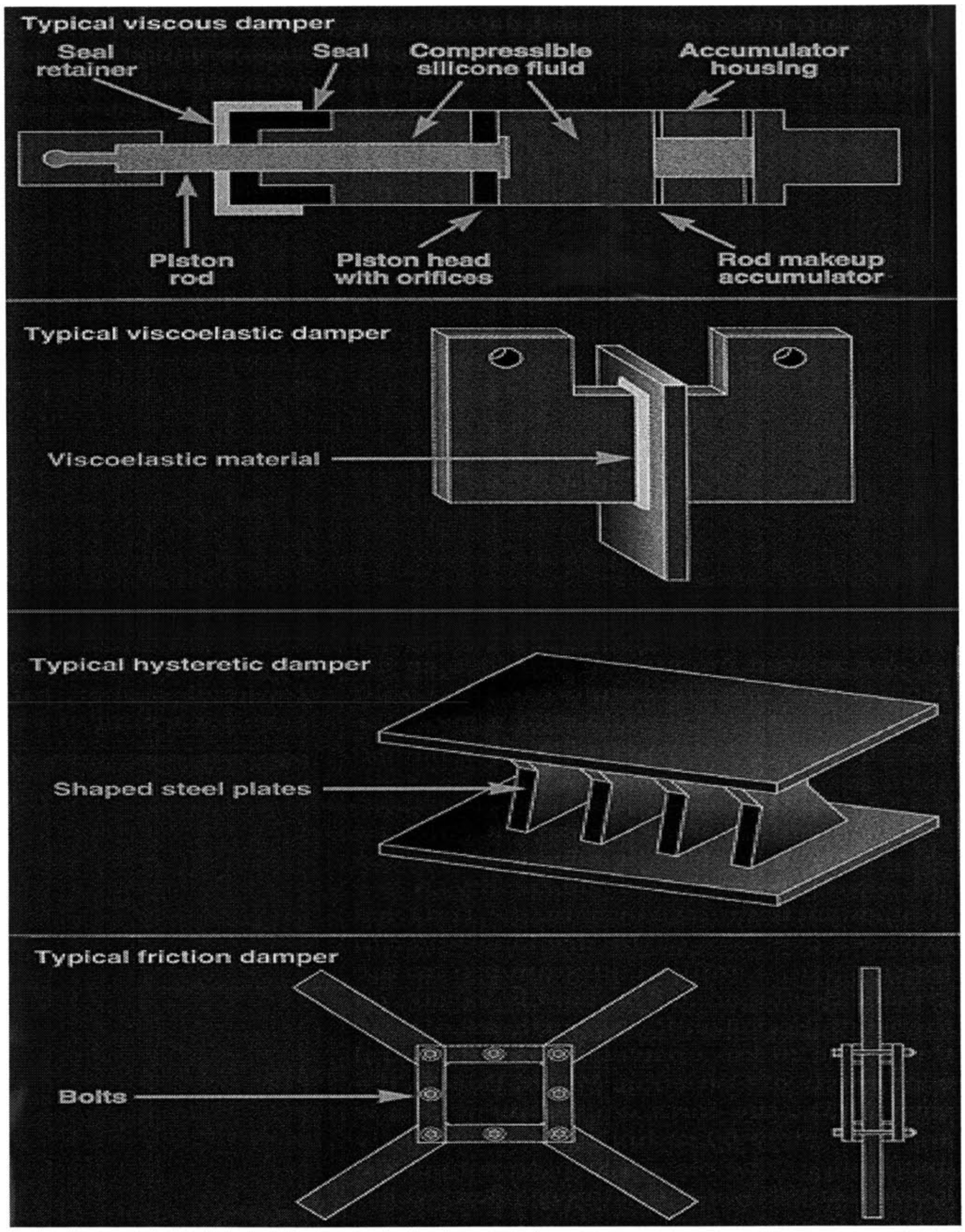

Figure 3.1: Passive Energy Dissipation Devices

3.1.1 Viscous Fluid Dampers

It is possible to dissipate earthquake induced energy and to reduce floor accelerations and story shears by installing viscous fluid dampers throughout the structure.

Viscous fluid dampers introduce damping forces which are 90 degrees out-of-phase with the displacement-driven forces, so the forces are combined in a vector sense, i.e. added in a SRSS manner. Viscous fluid damper forces also do not significantly increase the axial column forces that are in-phase with column bending moments.

Adding viscous fluid dampers to a building does not significantly change its natural period. Damping ratios up to 20% have been used in some recent dampers. In this way, the acceleration and the displacement of the building are greatly reduced, and accordingly the damage is limited.

The major manufacturer of viscous fluid dampers in the United States is Taylor Devices, Inc. [18]. Its viscous fluid damper consists of a stainless steel piston with bronze orifice head and an accumulator. It is filled with silicon oil. The viscous fluid damper dissipates the energy by pushing fluid through the orifice producing a damping pressure, which creates a damping force.

The performance characteristics of viscous devices closely match the mathematical linear viscous damping assumptions. By using the original structural stiffness values and the properties of these types of devices, an equivalent damping for the structural system can be established.

The force in the viscous fluid damper may be expressed as

$$F = C \times |v|^n \times \operatorname{sgn}(v) \tag{3.1}$$

where

v - velocity of piston rod

C - constant

n - coefficient in the range of approximately 0.3 to 1.0

The structural viscous fluid dampers are generally designed for a n value of 1.0.

3.1.2 Viscoelastic Dampers

Viscoelastic dampers have been used as energy dissipation devices for structures against wind induced vibrations. They have been installed in tall buildings, such as the World Trade Center in New York, Columbia Sea First Building and Two Union Square Building in Seattle. Interest has recently been directed to the feasibility of applying viscoelastic dampers to structures for earthquake resistant design [15].

Analytical and experimental research [2, 5, 20, 32] has shown that the installation of viscoelastic dampers to a building can reduce its seismic response.

Viscoelastic materials used in structural application dissipate energy when subjected to shear deformation. A typical viscoelastic damper consists of viscoelastic layers bonded to steel plates. The steel plates can be connected to braces. When the structural vibration induces relative motion between the outer steel flanges and the center plate, shear deformation and hence energy dissipation takes place.

The stress-strain relationship of viscoelastic dampers under harmonic motions can be expressed as

$$\gamma = \gamma_0 \sin \omega t \tag{3.2}$$

$$\sigma = \sigma_0 \sin(\omega t + \delta) \tag{3.3}$$

where

γ_0 – strain amplitude

σ_0 – stress amplitude

δ – the phase angle led by the stress.

So the stress and strain of viscoelastic dampers under harmonic motion is out-of-phase. Even though the structural response is elastic, hysteresis loops form (Fig. 3.2) due to this out-of-phase characteristic. The area enclosed in the hysteresis loops is the energy dissipated by the viscoelastic dampers during one cycle of oscillation.

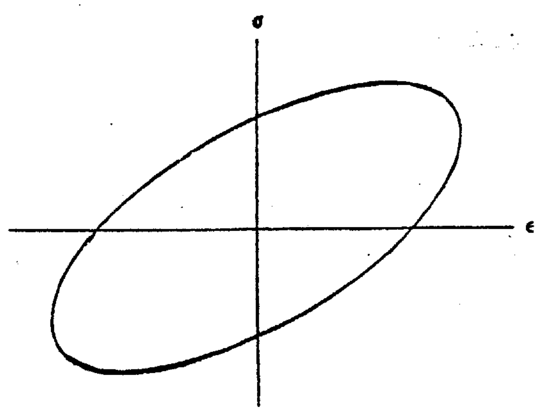

Figure 3.2: Stress-Strain Relationship: A Hysteresis Loop

The above equations can be written as

$$\sigma = \gamma_0(G_1 \sin\omega t + G_2 \cos\omega t) \tag{3.4}$$

where

G_1 - shear storage modules

G_2 - shear loss modulus

The ratio of G_1 to G_2 is the loss factor η.

Mechanical properties of viscoelastic dampers depend strongly on vibrational frequency and ambient temperature [6]. As the vibrational frequency is increased, the values of G_1 and G_2 become larger, and as the ambient temperature is increased, they become smaller. The energy dissipation capacity decreases with increasing temperature. However, the loss factor is insensitive to moderate changes in the frequencies and temperatures.

For a viscoelastic damper with total shear area A and total thickness h, the corresponding force-displacement relationship for periodic excitation is

$$F(t) = k_d(\omega)X + c_d(\omega)\frac{dX}{dt} \tag{3.5}$$

in which

$$k_d(\omega) = \frac{AG_1(\omega)}{h} \tag{3.6}$$

$$c_d(\omega) = \frac{AG_2(\omega)}{\omega h} \tag{3.7}$$

where

G_1 - shear storage modules

G_2 - shear loss modulus

A linear structural system with added viscoelastic dampers remains linear with dampers contributing to increased viscous damping as well as lateral stiffness.

It should also kept in mind that while stiffening effect may lead better control of lateral deformation, it may also lead to larger seismically induced forces for various ground motions. In such cases, the positive effect of added damping might be diminished by the stiffening effect.

Another drawback of viscoelatic damping devices is that they cause in-phase column stresses.

3.1.3 Friction Dampers

Friction is another helpful mechanism for dissipating the energy. The application of the friction dampers is primarily associated with the use of Pall friction devices in Canada and Sumitomo friction dampers in Japan. Pall friction devices have been installed to the headquarters building of Canadian Space Agency and New Concordia University Library

Building in Montreal [7]. Sumitomo friction dampers have been used for the seismic design of 31-story steel frame Sonic office building in Omiya City [15].

The Pall friction devices can be installed in a structure in a cross-braces frame. A plot of the typical cyclic response is shown in Figure 3.3 [7]. The system consists of a special mechanism containing slotted friction brake lining pads introduced at the intersection of the frame cross-braces. The damper is designed not to slip during wind storms or moderate earthquakes. It is designed to slip only during severe seismic excitation at a predetermined load before any inelastic deformation of the structural members. In this way the seismic energy can be dissipated mechanically. Slipping of the device changes the structure's natural frequency and allows to alter its fundamental dynamic characteristics during a severe earthquake.

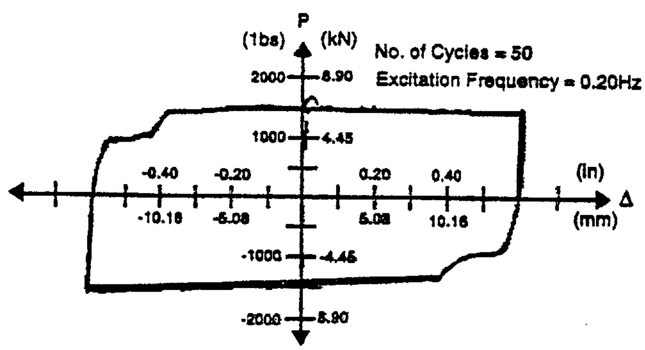

Figure 3.3: Force-Displacement Response of Pall Friction Device

The mechanical energy dissipation in a friction damped braced frame is equal to the product of the slip load by the total slip travel summed over all devices.

The damping ratio of friction dampers is around 10% of critical. They cause in-phase column stresses, and they don't allow the building to return into its original position after an earthquake.

3.1.4 Added Damping and Stiffness Devices

Yielding of a metal can be used for the dissipation of energy input to a structure from an earthquake. Supplemental damping devices have been installed in a building in San Francisco [9]. The devices used are Added Damping and Stiffness (ADAS) elements, which consist of multiple X-steel plates that deform plastically during a severe earthquake and dissipate energy through bending of the steel plates caused by interstory drift. The plates are made of ductile mild steel, are sized to respond elastically for wind forces, and to deform inelastically, dissipating energy during earthquakes. The shape of the devices is such that yielding occurs over the entire length of the device. This is achieved by the use of rigid boundary members, so that the X-plates are deformed in double curvature.

ADAS elements provide stiffness up to the point at which steel yields. They can be installed anywhere within the architectural framework of a building, at both interior and exterior walls. In the design of frames with ADAS elements, it is important to select appropriate values of the ADAS device parameters, such as the device yield force, device yield displacement, the stiffness ratio of the ADAS element stiffness to the frame story stiffness.

3.2 Base Isolation

Base isolation is a design strategy relying on using a seismic isolation system to separate the building from the horizontal component of the ground motion.

Base isolation has become a widely accepted strategy for achieving improved seismic protection of structures since the completion of the first seismically isolated building in the United States in 1985 [1].

The use of base isolation can limit the economic losses after a severe earthquake by reducing the ductility requirements for reinforced concrete structures.

A typical base isolator consists of an isolation mechanism and a damping mechanism. The isolation mechanism elongates the structure's period of vibration and shifts it from the peak response range of the acceleration spectrum to the low response range, which limits the amount of seismic shear developed at the base of the structure (Fig. 3.4). The damping mechanism suppresses the isolator's spectral displacement and improves the base shear reduction efficiency of the isolator mechanism. Both mechanisms together reduce the horizontal seismic force acting on the building which results in reducing of the structural deformations in the building. This will enable the structure to remain below its elastic limit during a strong earthquake.

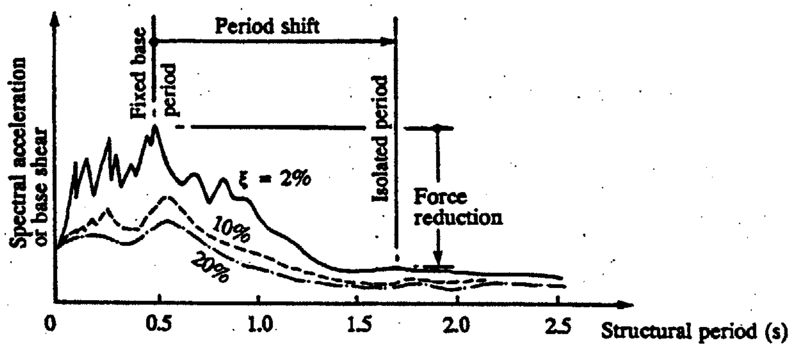

Figure 3.4: Effect of Period Shift on Design Forces

It is well known that a flexible structure experiences small acceleration and large displacements, and a very rigid structure experiences small relative displacements but acceleration equal to the ground acceleration. A base-isolated structure has both small interstory drifts and small floor accelerations. Interstory drifts are reduced because of the rigid body motion of the superstructure, whereas the floor accelerations are reduced because of the lengthening of the fundamental period as a result of the installation of a flexible system, i.e. base isolation system, between the ground and the superstructure.

The main constraint in the practical application of base isolation is the large relative displacements between the superstructure and the ground. Another constraint is the potential uplift of columns in an isolated building. During severe earthquakes, the lateral seismic forces and resulting moments may cause axial loads larger than gravity loads.

Most commonly used seismic isolation devices are sliding systems and elastomeric bearings (lead rubber bearing and high damping rubber bearings).

Sliding systems are based on friction. They allow transmission of shear force up to a specific level, beyond which sliding occurs and transmission is prevented. Such systems are designed for allowing a very low base shear force. This doesn't depend on the severity of the earthquake since the transmitted force is based on the friction coefficient. Sliding systems are very efficient to reduce the effects of severe earthquake excitation, but they need a restoring force mechanism to be effective. Permanent offset of the isolated structure from its original position may result after an earthquake, which decreases the displacement to be accommodated during a future seismic action.

The most popular seismic isolation systems use elastomeric bearings. They consist of thin rubber sheets which are bonded on thin steel plates and are combined with an energy dissipation mechanism such as lead core (Fig. 3.5).

They are very stiff vertically, being several times the shear stiffness. In this way they can sustain the structure's gravity loads with only minimal settlement.

The shear modulus of the elastomer depends on strain amplitude, so the bearing can provide initial resistance to wind or minor earthquakes as well as isolation for a major earthquake. At low strains, the modulus is 3-4 times greater than that at high strains. Softening occurs with increasing strain, and the desired isolation is achieved.

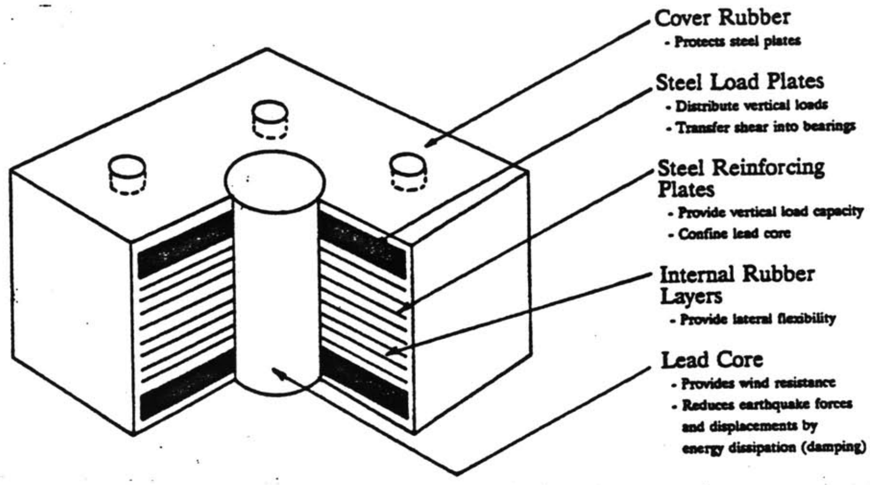

Figure 3.5: Elastomeric Bearing with Lead Plug Damper Included

Lead rubber bearings consist of thin layers of natural rubber sandwiched between steel plates. A lead cylinder plug is firmly fitted in a hole at its center to deform in pure shear. Lead is a crystalline material, so it changes its structure temporarily under deformations beyond its yield point, and regains its original structure and elastic properties as soon as the deformation is removed. When the lead is forced to deform plastically in shear, it dissipates the energy hysterically.

High damping rubber bearings are made of high damping rubber sandwiched between steel plates. High damping rubber gets its damping property because of the addition of special fillers, particularly carbon. The filler increases the inherent damping properties of rubber, but does not affect its mechanical characteristics.

The William Clayton Building in Wellington, New Zealand, is a four-story in-situ reinforced concrete frame completed in 1982. It was the first building to be base-isolated on lead rubber bearings. The extra cost of lead rubber bearings and the extra foundation beams was about 3.5% of the total building's cost, but due to the beam-column joint shear reduction and seismic gap detailing some savings were made [3].

3.3 Active Control

Active control like the other modern seismic tools can be used to increase damping and to modify the natural period of structures. With an active control system, it is possible to modify the dynamic behavior of a structure by means of an automatic control system which consists of sensors, controllers, and actuators, through some external energy supply.

The response of the structural system or the external excitation or both are measured by the physical sensors, which can be optical, mechanical, electrical, or chemical. This information is sent to the controller, where necessary control forces are computed based on a given control algorithm. The actuators apply these control forces to the structure in a prescribed manner with the help of the external power source. These forces can be used to both add and dissipate the energy in the structure. A schematic representation of the basic configuration of an active structural control system is given in Figure 3.6.

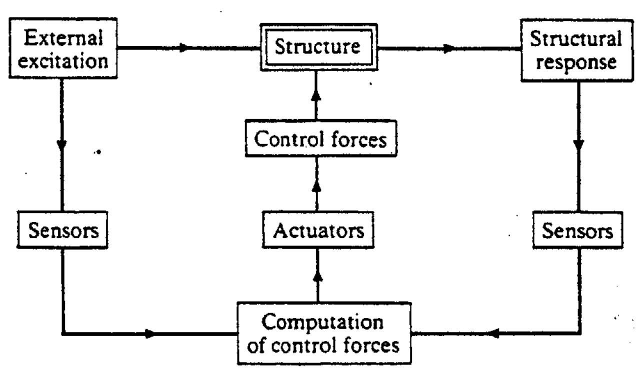

Figure 3.6: Schematic Diagram of Active Control

When only the structural response variables are measured, the control configuration is referred to as closed loop control (Fig. 3.7). The structural response is continually monitored, and this information is used to make continual corrections to the applied control forces. When the control forces are regulated only by the measured excitation, this configuration is called open loop control (Fig. 3.8). Closed-open loop control is the configuration where the information on both the response quantities and excitation are utilized for control design

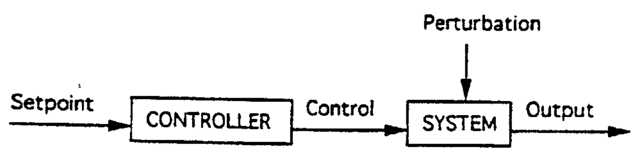

Figure 3.7: Open Loop Control

One of the advantages of active control is that it can be applied at the substructural level, e.g. to motion sensitive equipment or expensive secondary systems whose operating safety is very important.

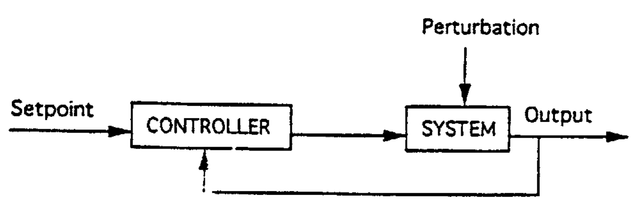

Figure 3.8: Closed Loop Control

If we model a building structure, on which such control forces are applied, by an n-degree of freedom lumped mass-spring-dashpot system, the equation of motion of the system is written as

$$M\frac{d^2}{dt^2}x(t) + C\frac{d}{dt}x(t) + Kx(t) = Du(t) + Ef(t) \tag{3.8}$$

where M, C, and K are the nxn mass, damping, and stiffness matrices, respectively, x(t) is n-dimensional displacement vector, f(t) is an r-dimensional vector representing applied load or external excitation, u(t) is the m-dimensional control force vector, and E nxr and D nxm are location matrices, which define locations of the excitation and the control forces, respectively.

If we assume that the closed-open loop control system is used, where the control force u(t) is designed to be a linear function of the measured displacement vector x(t), the velocity vector dx(t)/dt, and the excitation f(t), the control force vector takes the form

$$u(t) = K_1x(t) + C_1\frac{d}{dt}x(t) + E_1f(t) \tag{3.9}$$

where K_1, C_1, and E_1 are respective control gains which can be time-dependent.

The substitution of equation 3.9 into equation 3.8 yields

$$M\frac{d^2}{dt^2}x(t) + (C - DC_1)\frac{d}{dt}x(t) + (K - DK_1)x(t) = (E + DE_1)f(t) \tag{3.10}$$

If we compare equation 3.10 with equation 3.8 in the absence of control, it is clear that the effect of closed-open loop control is to modify the structural parameters (stiffness and damping), so that is can respond more desirably to the external excitation. The effect of the open loop component is a modification (reduction or complete elimination) of the excitation.

Two of the applications of the active structural control are active bracing system and active mass dampers.

Active bracing system consists of prestressed tendons or braces connected to a structure. The tendons are controlled by electrohydraulic servomechanisms.

Experiments have revealed significant decrease in structural motion under the action of the simple tendon system. In a single degree of freedom system a reduction of over 50% of the maximum relative displacement has been achieved [29].

The study with active mass dampers has been inspired basically from the passive tuned mass dampers, which have already been in use for the motion control of tall buildings. However, passive tuned mass dampers are generally tuned to the first fundamental frequency of the structure, so they are only effective if the first mode is the dominant vibrational mode. But, the vibrational energy is spread over a wider frequency when the structure is subjected to seismic forces. So active tuned mass damper should come into the picture.

Kyobashi Seiwa building is the first building in the world, which has an active control system [17]. Its active control is achieved with active mass dampers.

Chapter 4

Damage Controlled Design

4.1 Definition

Structural engineers are challenged to search for new and better methods to design structures to withstand extreme earthquakes and protect the occupants and equipment. Traditional earthquake-resistant design approaches focus on the strength of the structure resisting the lateral loads. Story drift limitations are established only to guard against unreasonably flexible structures.

Earthquake damage to a structure is not only associated with the seismicity of the region but also with the methodology used to design the structure. The cause of earthquake hazards is the interaction of earthquake ground motion with the built environment. The damage is a consequence of deformation rather than forces.

For many years, research has been focused on maximizing the ability of structural elements to absorb energy through inelastic deformation. Because of the inadequate strength of structural materials, engineers have been accepting the inelastic deformation of the building. But when the seismic design relies on inelastic deformation of the structural elements, it can only satisfy the life safety criterion, which is defined as the protection of occupants against injuries or loss of life. However, this building can not be reused after a strong seismic action, and now the focus is shifting to minimizing inelastic deformation and dissipating the energy induced to the structure by an earthquake in another way to reduce the damage.

Since experience with recent earthquakes has shown that life safety and prevention of collapse, which most of the seismic design codes are based on, are certainly very important and desirable, but not adequate in economic terms, other design criteria should be applied. There is a need to design, construct, and maintain structures with better damage control than at present if the economic consequences of recent earthquakes are considered. The motivation for damage controlled design is to limit the cost associated with not only the initial cost but also with the repair cost after an earthquake, i.e. life-cycle cost of a structure.

Damage controlled design is a design strategy where the desired performance (level of damage) of the structure is specified, and the design is performed accordingly. It seeks to control the damage experienced by a building during discrete seismic events which may occur. For many sites there is a spectrum of earthquakes, ranging from small magnitude events with negligible hazards, which have generally high probabilities of occurrence, to large magnitude events with considerable hazards, which have generally lower probabilities of occurrence. Applying the damage controlled design methodology to a structural system allows the structure to be used after a severe earthquake with reasonable repair cost. The goal is to minimize the earthquake related cost to the building owner. Economic considerations include, besides the cost related to damage repair, business interruption where applicable. It limits the potential damage to a tolerable level by properly selecting the structural properties of the members. The permissible damage level is judged in terms of repairability and cost of repair.

The philosophy is to satisfy owner-specific performance goals. It presents owners with various design options some of which not only fulfill the requirements of codes but also consider economic performance, including earthquake related costs. The design options vary from a design, which has the least damage with high initial value, to one having a low initial value and high damage cost. It allows owners to choose their own design performance.

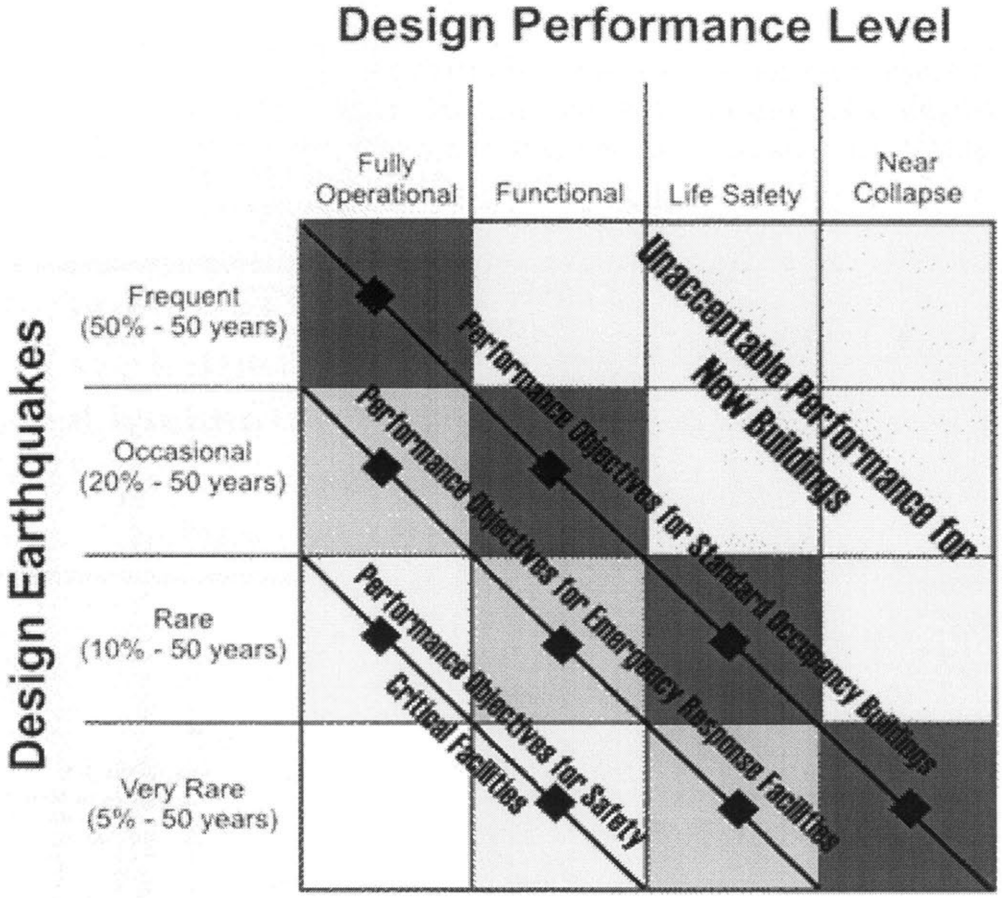

Figure 4.1: Vision 2000 Performance Objectives

Vision 2000 [28] is a project, which has been undertaken by the Structural Engineers Association of California (SEAOC) to establish a performance-based design procedure. The series of standard performance objective suggested by Vision 2000 is indicated in Figure 4.1. It suggests design levels related not only to life safety or collapse prevention, but also to functionality. Each diagonal line in the figure relates design performance levels and corresponding earthquake for a range of buildings classified according to usage. Table 4.1 contains descriptions of the various performance levels.

Performance Level	Description
fully operational	no significant damage has occurred to structural and nonstructural components. Building is suitable for normal intended occupancy and use.
functional	No significant damage occurred to structure, which retains nearly all of its pre-earthquake strength and stiffness. Nonstructural components are secure and most would function, if utilities available. Building may be used for intended purpose, albeit in an impaired mode.
life safety	Significant damage to structural elements, with substantial reduction in stiffness however, margin remains against collapse. Nonstructural elements are secured but may not function. Occupancy may be prevented until repairs can be instituted.
near collapse	Substantial structural and nonstructural damage. Structural strength and stiffness substantially degraded. Little margin against collapse. Some falling debris hazards may have occurred.

Table 4.1: Definitions of structural performance

A performance objective refers to the desired building behavior. A performance level is an expression of the maximum allowable damage to a structure due to a specific earthquake design level. The level of allowable damage depends on the mission of the building. A higher level of damage may be allowable in commercial buildings than in a hospital which is required to be fully operational after an earthquake. Another factor which influences the choice of the allowable damage is the economic impact of building loss. The loss of a building that has 100% of the company's inventory is less acceptable than the loss of a building that has only 10% of the company's inventory.

The selection of the performance objectives should be made by the owner, in consultation with the designer. The issues that need to be considered include the owner's expectations, seismic hazard exposure and economic analysis. The designer has to be able to explain to the owner what the damage implications for each performance level are. Mostly the owners are not aware that their conventionally designed structures may result in total loss or even collapse during a severe earthquake. If they knew this fact, they probably would be willing to pay for additional protection if the engineer is able to show them a cost-performance relationship, where the cost study includes the cost of repair. The opportunity to choose higher performance goals other than life safety should be given to an owner.

Most of the time, engineers have a difficult time explaining to the owners what they are buying, so owners can't relate the concept with the proposed performance levels. Thus, these concepts should be structured in terms of more meaningful phrases to the users. A probability of not exceeding a value for the desired life of the facility can be a meaningful term, which makes this design approach easier to implement.

Indicating the probability of exceeding (or probability of not exceeding) vs. overall cost for a design option should be presented, i.e. each design option will have several overall cost values, each of which has a certain probability of exceeding. Such terms are useful in evaluating each of the existing options. The owner has to be given the opportunity to select among them. This is a cost-benefit analysis. By presenting this issue in these terms, the concepts which may confuse the owners, such as randomness or uncertainties of the ground motion, are hidden such that he/she can make his/her decision more easily.

Damage is often described in qualitative terms. Many researcher agree that we need quantitative damage values. Since damage to a structure is associated with the deformation, the limit should be on the deformation of the structure, e.g. on the interstory drift, defined as the relative lateral displacement between two adjacent floors bounding the story of a building. Interstory drift is a very useful performance indicator, both for structural and nonstructural elements. Drift controlled design uses the estimated lateral displacements of structure under the expected design earthquake as a guide for determining the stiffness and strength. The key of this approach is the analytical evaluation of the maximum story drift.

The target design displacement capacity for a structural system can be determined from performance objectives and estimated demands. Vision 2000 suggests an interstory drift ratio of 1.5% for life safety, and 2% for near collapse levels. These values do not consider nonstructural damage. Performance goals should be based not only on the behavior of the structural system but also on the control of nonstructural and content damage.

To apply damage controlled design, a site seismicity study should be conducted to obtain the site acceleration as a function of the probability of occurrence. Structural analysis techniques are used to predict the structural response at different earthquake levels. Finally, the structural response needs to be correlated to damage.

4.2 Types of Damage

Damage to a structure subjected to an seismic motion may appear in many forms. The building damage caused by an earthquake consists of structural, nonstructural and contents damage. Nonstructural damage is made of architectural damage, and mechanical, electrical and plumbing (MEP) damage.

4.2.1 Structural Damage

Structural damage refers to damage to structural elements of the building system, which include vertical support components (columns, piers, bearing walls, foundations, etc.), horizontal span members (floor slabs, beams, girders, etc.), and any other structural element used for carrying the buildings's dead and live loads.

Structural damage occurs when a structural component is loaded beyond its capacity to resist a force. When a structural element is deformed and returns to its original state without permanent deformation, the element is behaving within its elastic range. When a material experiences deformation beyond its elastic range, i.e. in the inelastic range, it can not return to its original state, and is permanently deformed, i.e. it is damaged.

Structural damage in reinforced concrete structures may be due to excessive deformation, or it may be due to the accumulation of minor damages sustained under repeated load reversals. The damage may involve the cement-aggregate matrix, the reinforcing steel, or some combination of both. The concrete cracks and the reinforcement yields. So they cause permanent structural damage.

4.2.2 Nonstructural Damage

Nonstructural elements include all the architectural components found in a building system (e.g., cladding, ceilings, partitions, doors/windows, stairs, parapets, etc.) in addition to all mechanical, electrical and plumbing components (e.g., elevators, lights, piping, ducts, HVAC systems, escalators, security systems, etc.), whether on the exterior or interior.

It is widely accepted that architectural damage is correlated to interstory drift and MEP damage depends both on interstory drift and floor acceleration.

Examples of nonstructural building elements at high risk to damage caused by extreme building movements during a major earthquake are stiff, brittle infill walls, curtain window-walls rigidly fixed between structural components, continuous stairways between several floors, or inflexible pipe risers between two or more floors. A full-height partition element may be crushed between floors experiencing excessive interstory drift of the structural system. Nonstructural elements may be destroyed in a sudden explosive manner. Use of the ductile design approach has lowered the frequency of building collapses, but has increased the damage potential for nonstructural components.

4.2.3 Content Damage

The value of the building contents will vary greatly depending on the usage of the building, which may range from a simple office building to a sophisticated high-tech operation. The greatest cost is associated with high-tech buildings, such as data processing centers, chemical storage facilities, research laboratories, etc.

Content damage (Fig. 4.2) covers damage at any floor level to computers, valuable items, books in libraries, furniture, etc. It can be related to floor accelerations. In this high technology era, the economic losses associated with content damage may be much more significant than the losses due to damage related to the building itself.

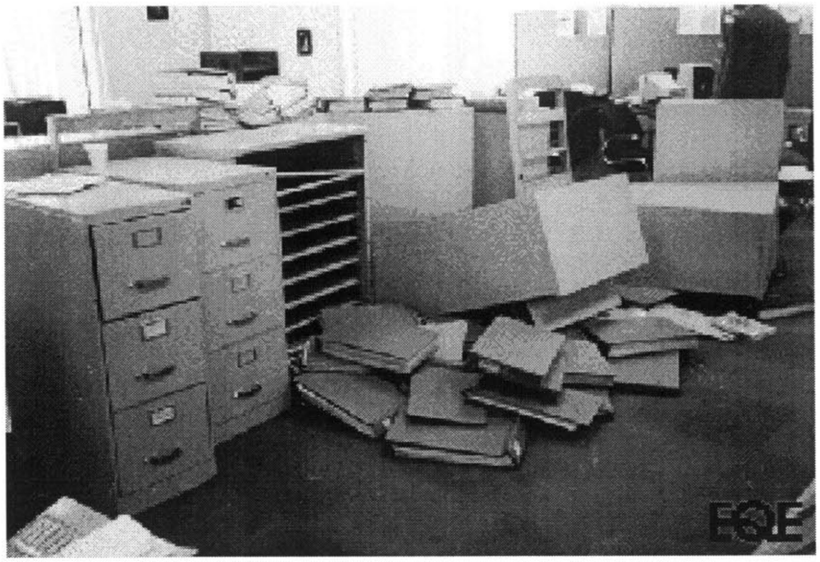

Figure 4.2: Content Damage [14]

4.3 Damage Estimation

The objective of damage controlled design is to develop design strategies which can limit economic losses. From the state of the art computer programs, structural response parameters such as interstory drift, floor acceleration, energy dissipation, etc. are obtained. To design to limit economic losses, we need design methodologies to predict or estimate losses from the expected structural response due to an earthquake. A relationship is needed between structural response and the monetary damage. It should be kept in mind that the total damage is the sum of the monetary damage in structural and nonstructural elements and contents.

A number of damage indices have been proposed to estimate the damage to reinforced concrete structures. Most of indices do not give a quantitative value of economic losses, and are used mainly to assist in the decision as to whether to retrofit an existing buildings. Among the proposed damage indices, the Park and Ang damage index is widely used [22].

This structural damage index is a simple linear combination of normalized deformation and energy absorption. It is defined as

$$DI = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE_h \tag{4.1}$$

where

d_m - maximum experienced deformation

d_u - ultimate deformation of the element

P_y - yield strength of the element

$\int dE_h$ - the hysteretic energy absorbed by the element during the response history

β – model constant parameter

This index is evaluated for each structural element of a building. Then, with the help of weighting factors, the damage of each story and then the damage of the total building is calculated. The interpretation of the overall damage index according to Park et al. [23] is presented in Table 4.2.

limit state damage index	degree of damage	damage (service) state
0.00	none	undamaged
0;20-0.30	slight	serviceable
0.50-0.60	minor moderate severe	repairable unrepairable
>1.00	collapse	collapse

Table 4.2: Interpretation of overall damage index

In order to apply damage controlled design to new buildings, one needs a relationship between the structural response and the economic losses associated with structural, nonstructural, and content damage. The engineer should be able to present the owner the expected life-cycle costs in a probabilistic format for each design option. The damage ratio defined by Hasselman and Wiggins can be used for structural damage losses[12], for nonstructural damage loss and content damage loss, the damage ratio proposed by Gunturi and Shah [11] is appropriate.

Hasselman and Wiggins studied the correlation between interstory drift and expected structural damage for both concrete and steel buildings by using the large amount of data on the seismic performance of buildings in the Los Angeles area, which had been provided by the 1971 San Fernando Earthquake. Using Bayesian statistics, they combined actual damage data with estimates of structural damage, carried out a regression analysis on the available damage data (mostly low damage state), and correlated the data for the higher damage states with estimates of experts. The actual earthquake damage was transformed into a damage ratio, DR, defined as the ratio of the damage cost to the replacement value. Their proposed relationship is as follows:

$$\log DR = \log DR_c + \left(\frac{\log DR_c - \log DR_t}{\log d_c - \log d_t}\right) \times (\log d - \log d_t) \tag{4.2}$$

DR - Damage Ratio

d - Interstory drift to story height ratio

DR_c -Damage threshold of 50%

DR_t-Damage threshold of 0.5%

d_c -Interstory drift to story height ratio corresponding to DR_c

d_t -Interstory drift to story height ratio corresponding to DR_t

Figure 4.3 shows the relationship between structural damage ratio and interstory drift for the case where d_c=0.015 and d_t=0.00085 for a reinforced concrete frame building.The same relationship is plotted in Figure 4.4 for steel frame building where d_c=0.05 and d_t=0.003.

Most of time the nonstructural damage is more severe than the structural damage [10, 24, 30, 31]. Since nonstructural damage depends on the interstory drift of a building, this value becomes the important factor for controlling the damage. Using a deterministic approach, Gunturi and Shah [11] correlated the interstory drift to nonstructural damage. They asked experts to specify the required value based on their experience.Their proposed nonstructural damage vs. interstory drift relationship is plotted in Figure 4.3; the contents damage vs. floor acceleration relationship is shown in Figure 4.5.

The interstory drift is a very useful performance indicator. The important component of drift will depend on the evaluation objective, considering that interstory drift may be caused by shear distortion within the story, cumulative flexural rotation (e.g. in walls)., and rotation at the bottom of the structure due to foundation flexibility. Also the floor acceleration is an important performance indicator for building contents.

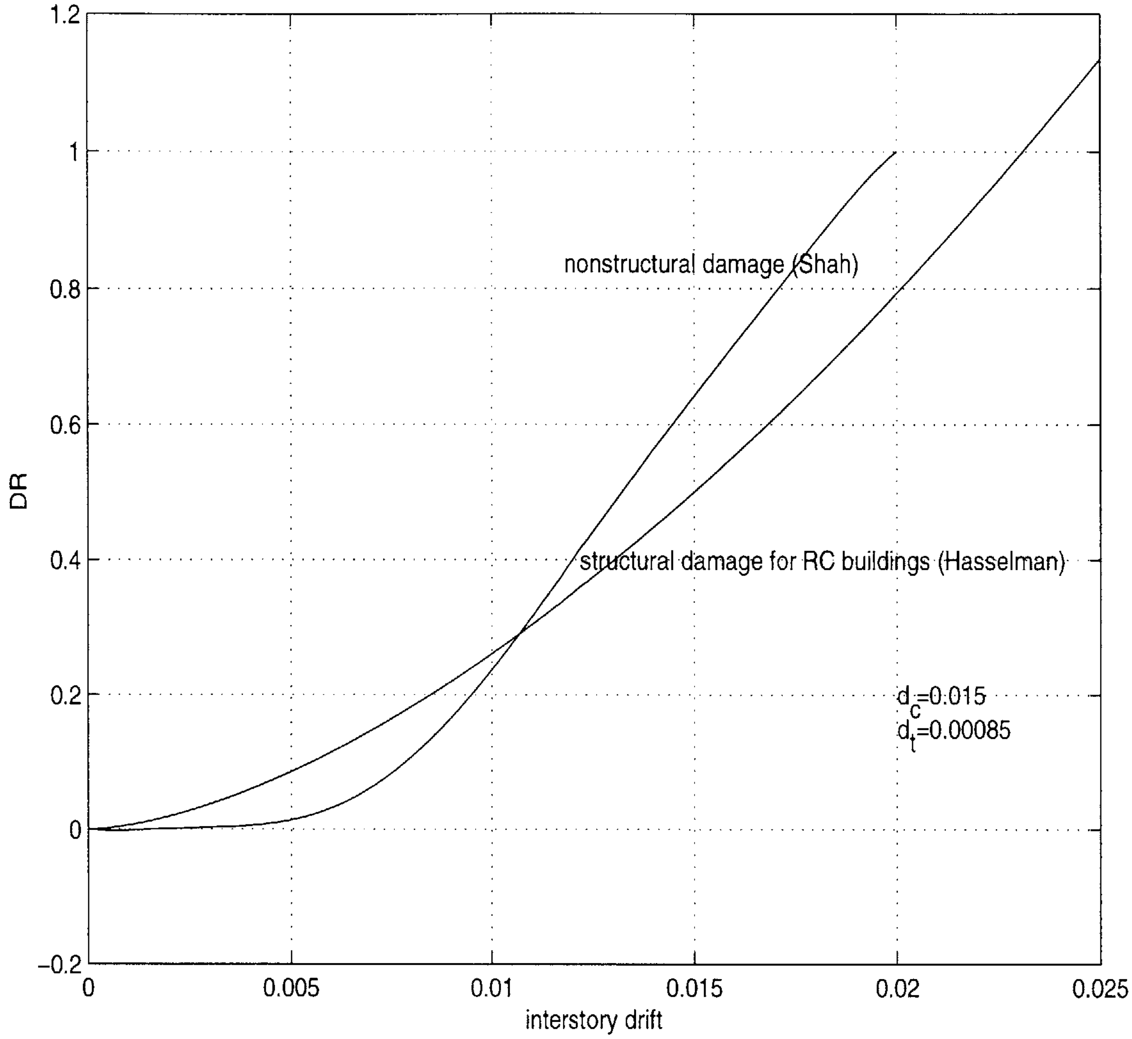

Figure 4.3: Relationship between damage ratio and structural and nonstructural damage for reinforced concrete buildings

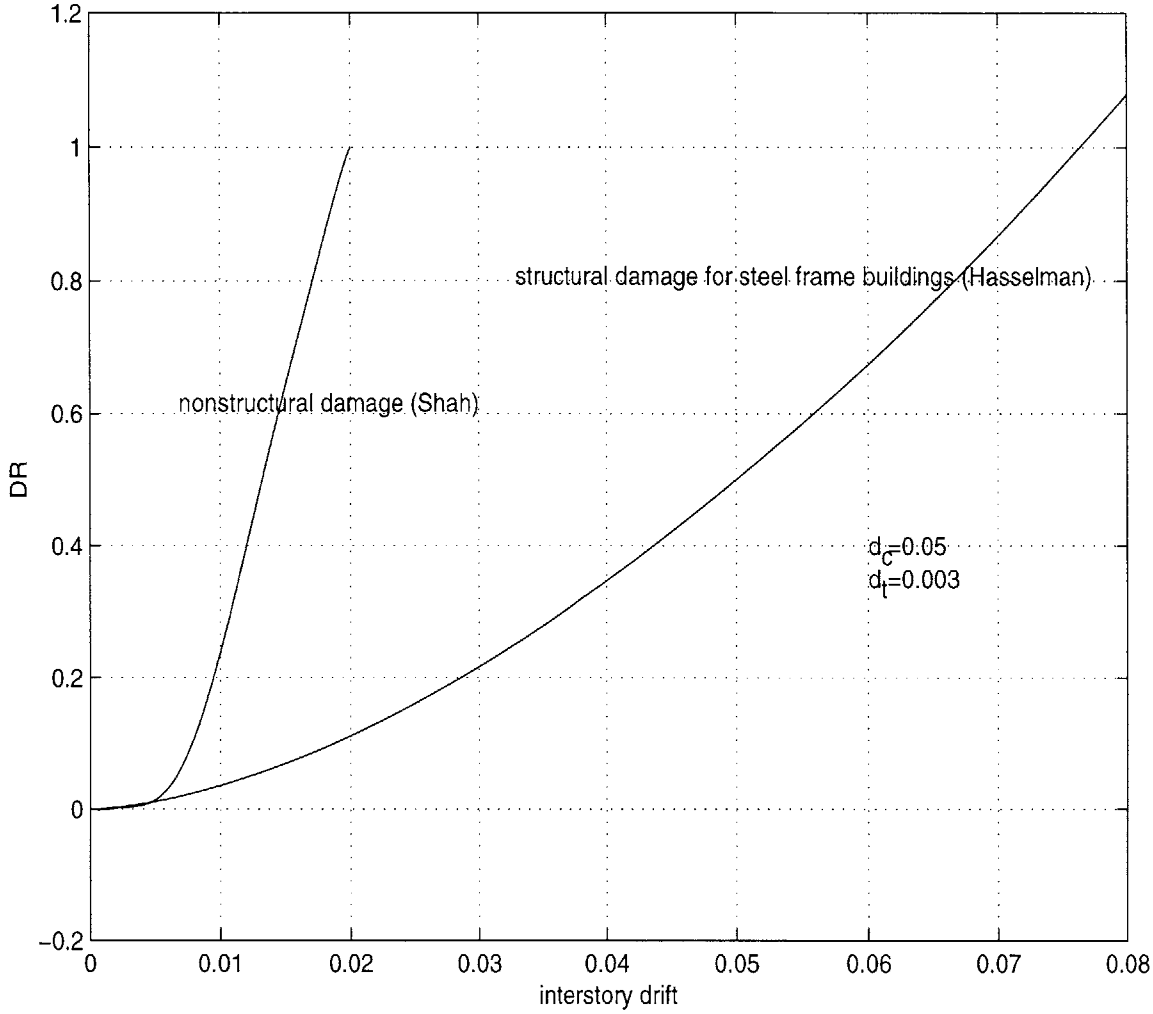

Figure 4.4: Relationship between damage ratio and structural and nonstructural damage for steel frame buildings

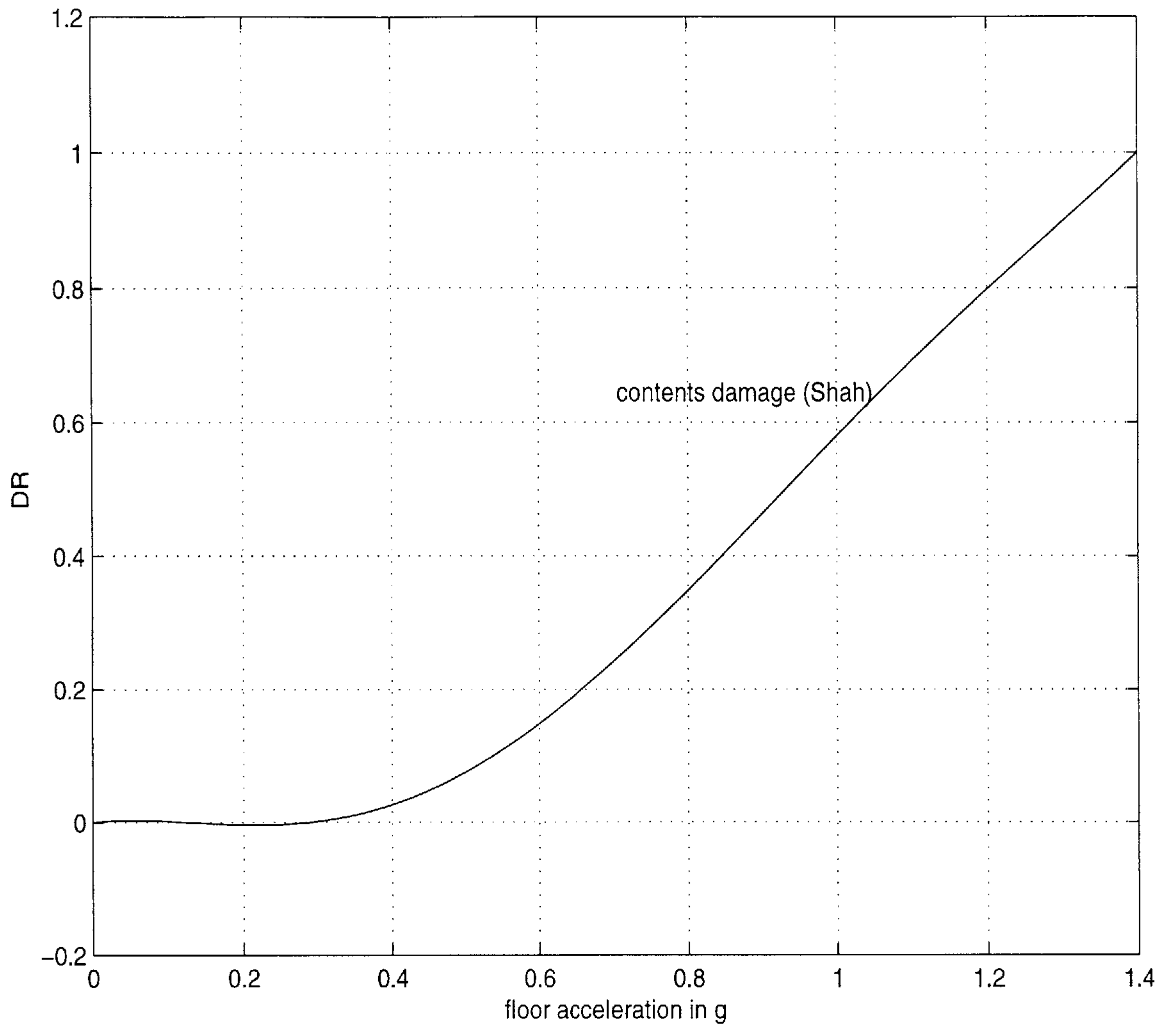

Figure 4.5: Relationship between damage ratio and content damage

Chapter 5

Application

5.1 Structural Analysis Software

In order to be able to present to the owner the life-cycle cost of each design option, the repair cost of the structure for various levels of earthquake needs to be calculated. The repair cost depends on the structural response. A computer program called IDARC [33] (Inelastic Damage Analysis of Reinforced Concrete Structures) developed by NCEER (National Center for Earthquake Engineering Research renamed in 1998 as MCEER Multidisciplinary Center for Earthquake Engineering Research) was used to generate the non-linear time history of the structural response. Significant features included in the program are:

- Hysteretic characteristics in the beam and column moment-curvature relationships

- Stiffness degradation, strength deterioration, and pinching effects in the hysteretic behavior of beams and columns

- Effect of axial force in the column moment-curvature relationship

- Effect of confinement of concrete

- Moment-curvature relationships are based on actual inelastic stress-strain relationships for both the concrete and the longitudinal reinforcing steel

- P-Δ effects in the calculation of the dynamic response of the overall frame structure.

Example of input and output files are listed in Appendix A.

5.2 Design Examples

Two design options for a 5 story-3 bay building are proposed and compared as an illustration of the damage controlled design approach. The first option is the conventional ductile design approach. The second option employs viscous dampers located in the diagonal of each story. A typical frame for each option is shown in Figure 5.1. The design for the first option is based on the requirement that the maximum interstory drift be equal or less than 0.025 for a design earthquake having a 475 year return period. The second design is based on multiple criteria: i) the maximum interstory drift for a very rare earthquake with return period of 1000 years be less than 0.02, ii) the maximum interstory drift for a rare earthquake with a return period of 475 years be less than 0.015, iii) the maximum interstory drift for a moderate earthquake with a return period of 225 years be less than 0.01, and iv) the maximum interstory drift for a frequent earthquake with a return period of 43 years be less than 0.0025.

The site acceleration probability curve used for this design example is plotted in Figure 5.2. The corresponding return periods of the probability of not exceeding is given in Table 5.1 [25].

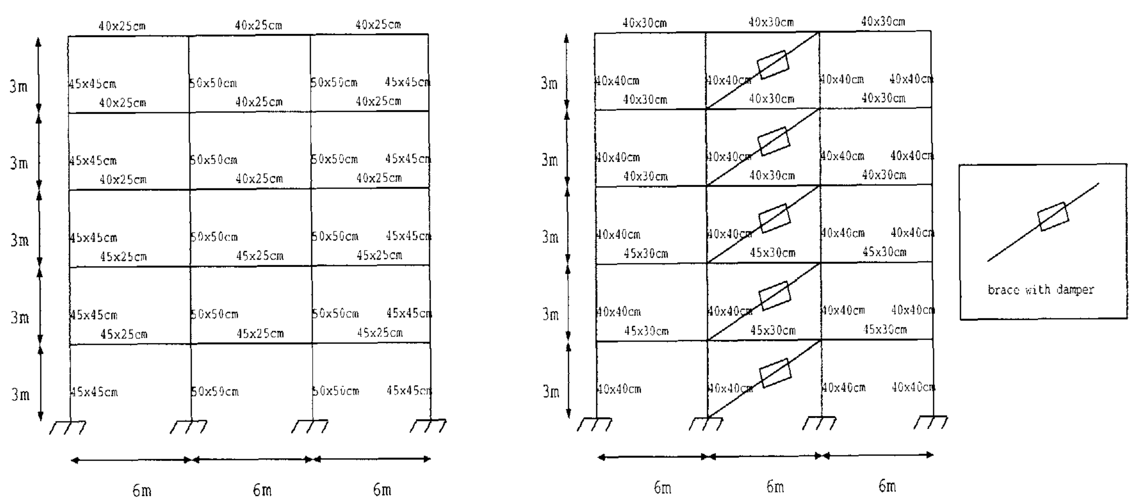

Figure 5.1: Typical Frames of both Design Options

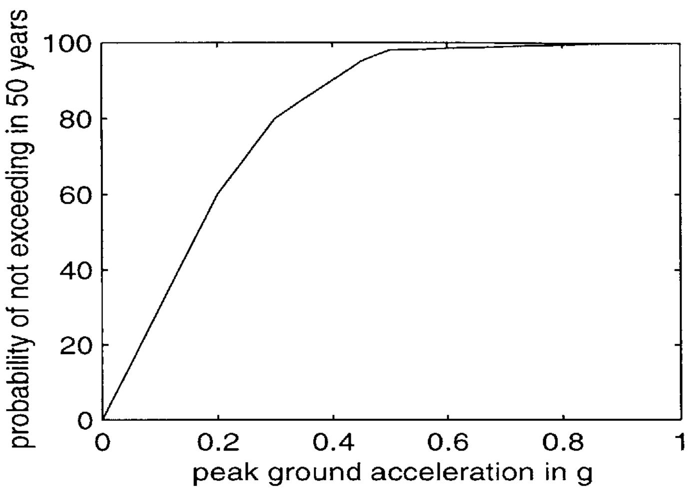

Figure 5.2: Site Acceleration Probability

Peak Ground Acceleration	Probability of not being exceeded in 50 years	Return Period
0.1g	30	43 years
0.15g	45	65 years
0.2g	60	100 years
0.25g	70	140 years
0.3g	80	225 years
0.35g	85	340 years
0.4g	90	475 years
0.45g	95	1000 years
0.5g	98	2500 years

Table 5.1: Return Periods

Sixteen acceleration time history records have been used. They are plotted in Figures 5.3 to 5.18. These strong motion records are scaled from 0.1g peak ground acceleration (PGA) to 0.5g PGA with 0.05g increments. Many time history have been used, because the maximum structural response, particularly the inelastic response, depends on the ground motion. The maximum structural response is calculated for each acceleration time history at each of these 9 peak ground accelerations using IDARC, and the mean value is taken for each PGA.

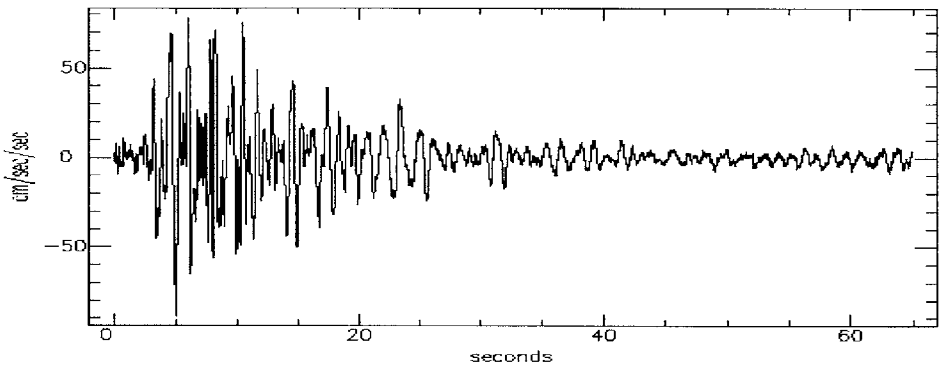

Figure 5.3: A Strong Motion Record from Coalinga CA 1983 Earthquake [13]

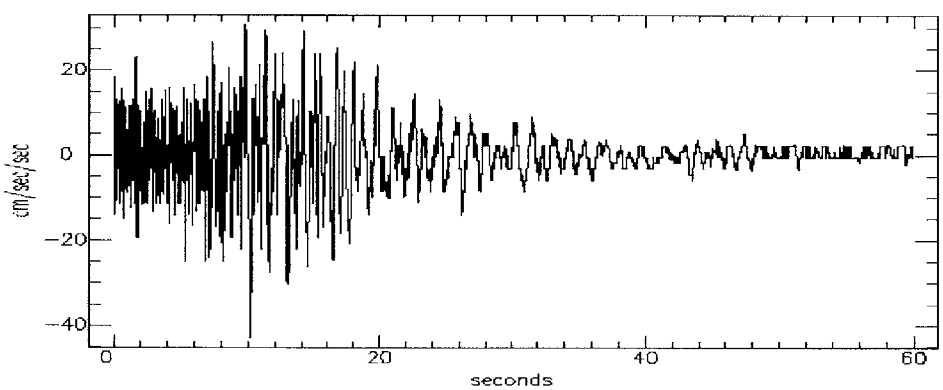

Figure 5.4: A Strong Motion Record from Coalinga CA 1983 Earthquake [13]

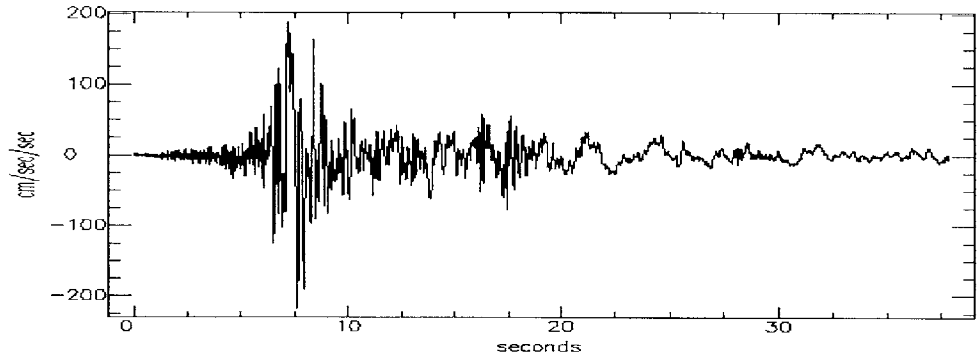

Figure 5.5: A Strong Motion Record from Imperial Valley CA 1979 Earthquake [13]

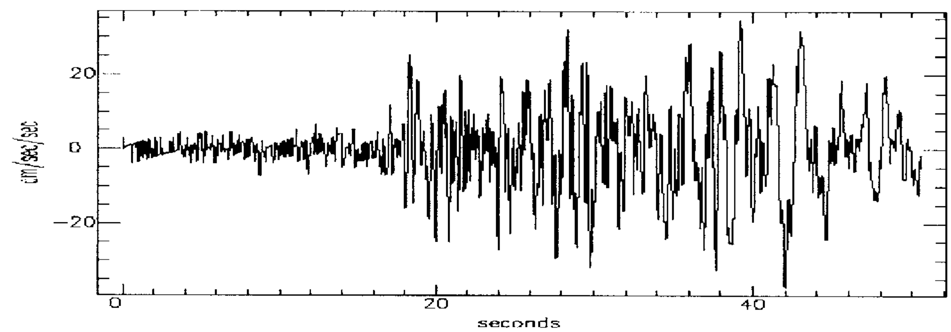

Figure 5.6: A Strong Motion Record from Landers 1992 Earthquake [13]

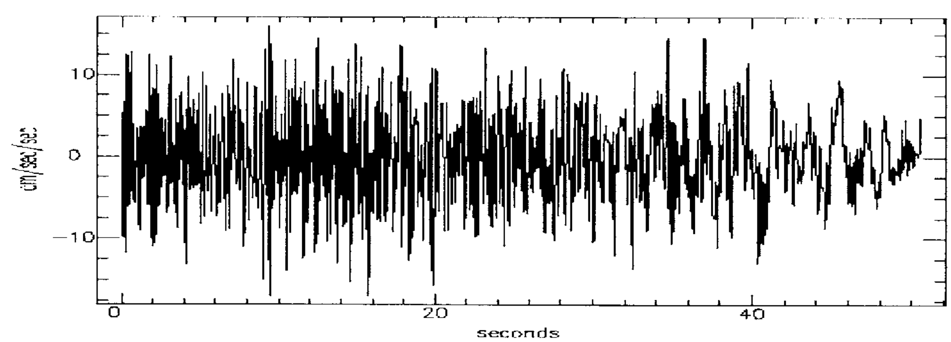

Figure 5.7: A Strong Motion Record from Landers 1992 Earthquake [13]

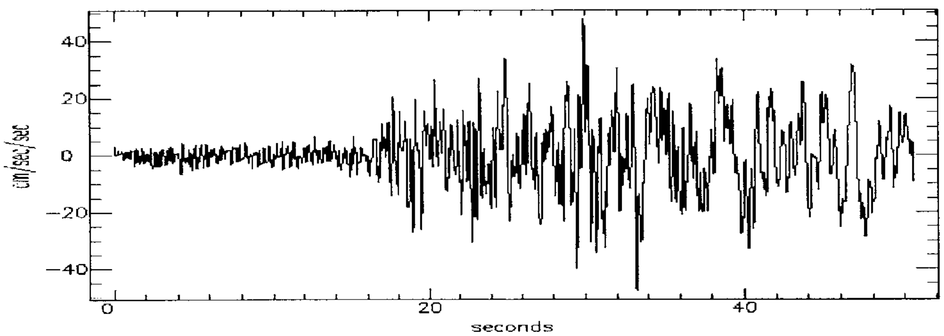

Figure 5.8: A Strong Motion Record from Landers 1992 Earthquake [13]

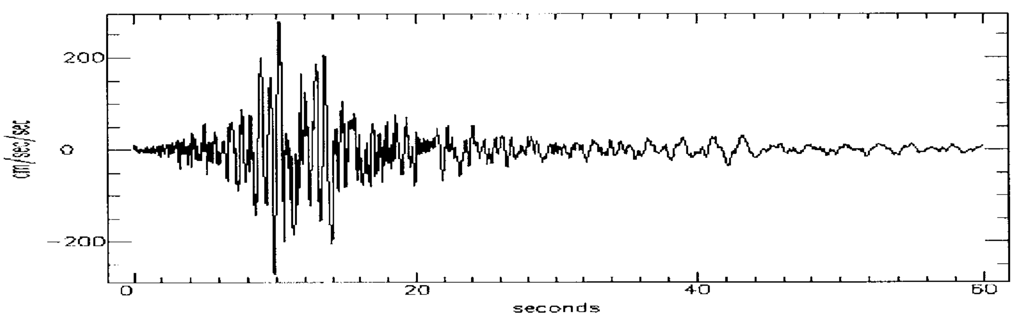

Figure 5.9: A Strong Motion Record from Loma Prieta 1989 Earthquake [13]

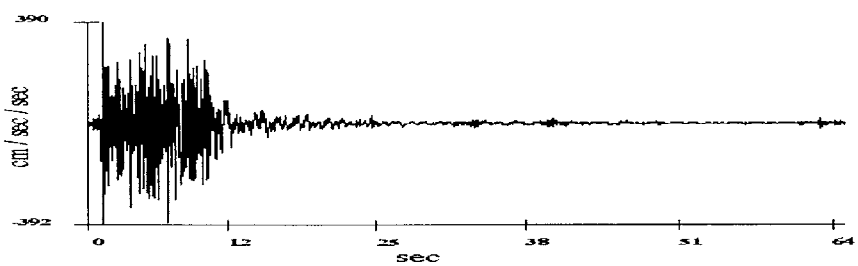

Figure 5.10: A Strong Motion Record from Mammoth Lakes CA 1980 Earthquake [13]

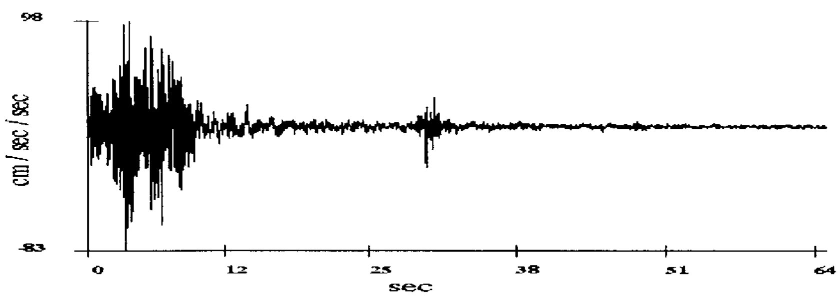

Figure 5.11: A Strong Motion Record from Mammoth Lakes CA 1980 Earthquake [13]

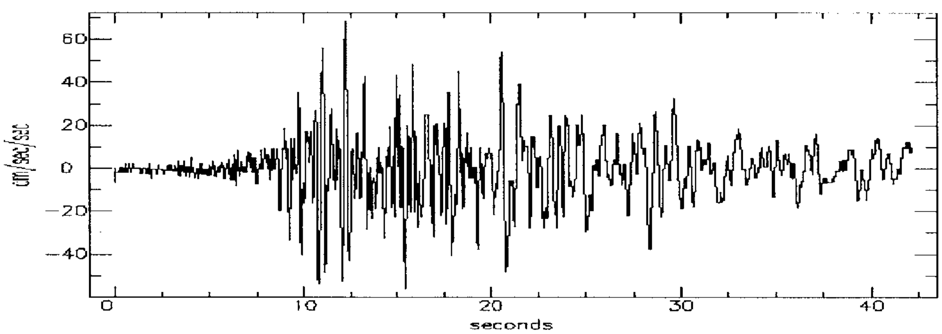

Figure 5.12: A Strong Motion Record from Northridge 1994 Earthquake [13]

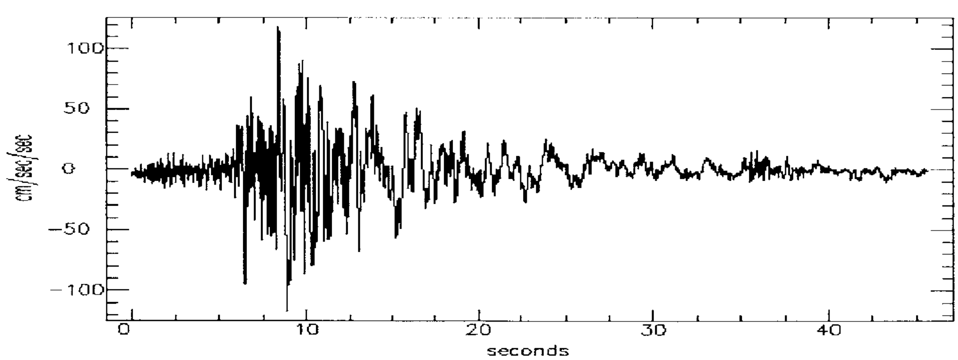

Figure 5.13: A Strong Motion Record from San Fernando 1971 Earthquake [13]

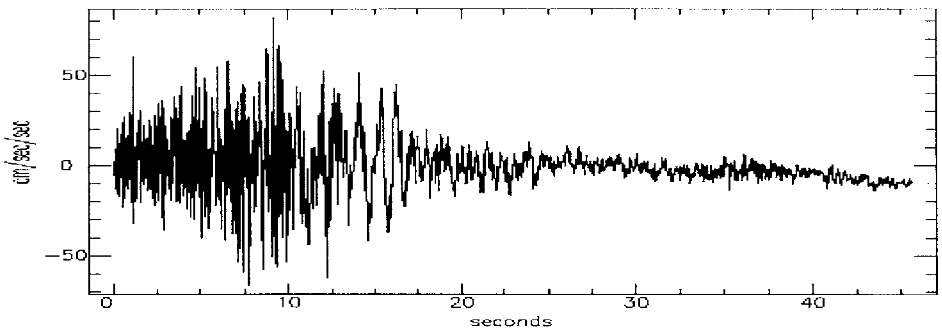

Figure 5.14: A Strong Motion Record from San Fernando 1971 Earthquake [13]

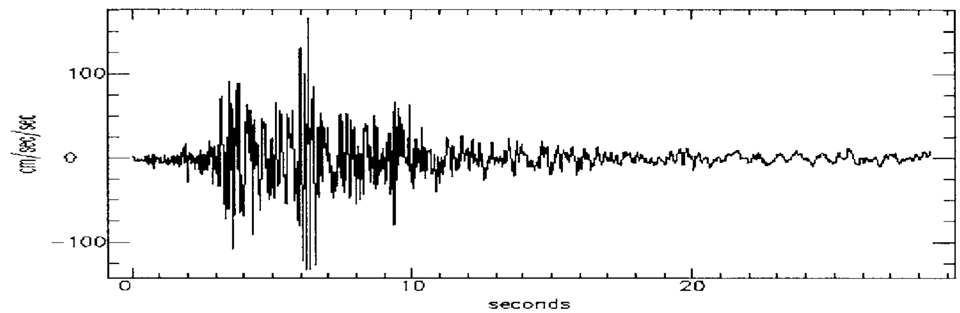

Figure 5.15: A Strong Motion Record from Westmorland CA 1981 Earthquake [13]

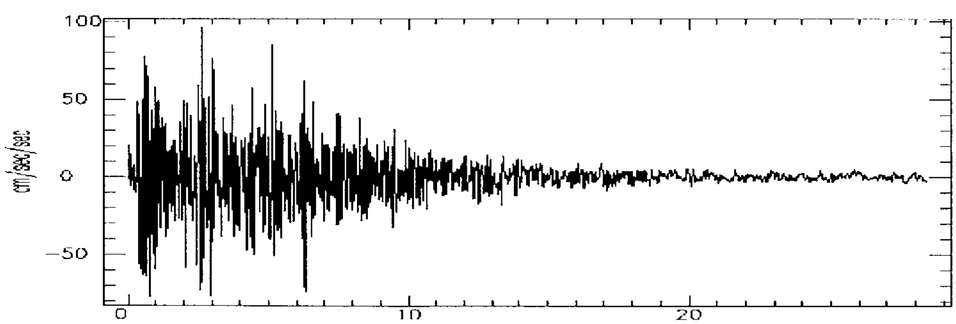

Figure 5.16: A Strong Motion Record from Westmorland CA 1981 Earthquake [13]

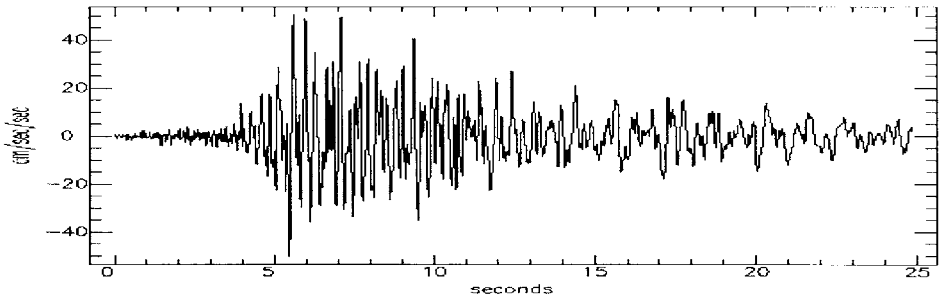

Figure 5.17: A Strong Motion Record from Whittier Narrows 1987 Earthquake [13]

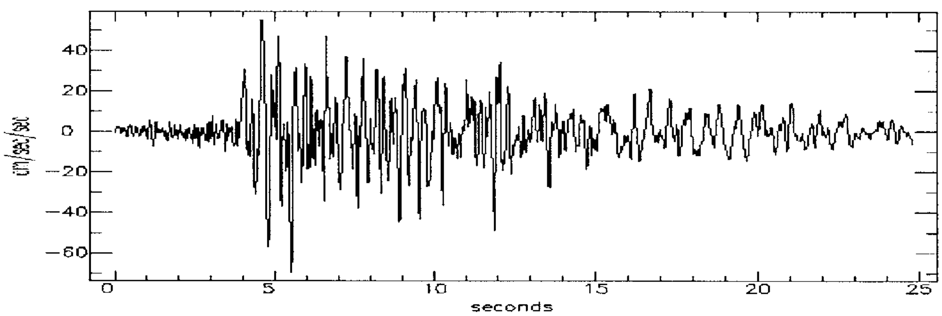

Figure 5.18: A Strong Motion Record from Whittier Narrows 1987 Earthquake [13]

5.3 Damage Estimation

The structural, nonstructural, and content damages are estimated from the mean structural response. The mean structural response and the damage ratios, which are found with the help of Figure 4.3 and 4.5, are given in Tables 5.2 to 5.19. Tables 5.2 to 5.10 apply for the conventional design option, and the other tables are based on using viscous dampers.

Table 5.2: Damage Ratios when PGA 0.5g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0359	0.5486	1.0000	1.0000	0.1081
4	0.0357	0.3504	1.0000	1.0000	0.0112
3	0.0334	0.4730	1.0000	1.0000	0.0599
2	0.0289	0.5397	1.0000	1.0000	0.1018
1	0.0153	0.4786	0.5161	0.6651	0.0630

Table 5.3: Damage Ratios when PGA 0.45g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0296	0.5191	1.0000	1.0000	0.0877
4	0.0296	0.3298	1.0000	1.0000	0.0066
3	0.0282	0.4415	1.0000	1.0000	0.0439
2	0.0249	0.5009	1.0000	1.0000	0.0761
1	0.0133	0.4258	0.4123	0.5058	0.0368

Table 5.4: Damage Ratios when PGA 0.4g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0243	0.4950	1.0000	1.0000	0.0725
4	0.0244	0.2942	1.0000	1.0000	0.0008
3	0.0231	0.4022	0.9995	1.0000	0.0273
2	0.0201	0.4739	0.7996	1.0000	0.0604
1	0.0114	0.3936	0.3219	0.3482	0.0242

Table 5.5: Damage Ratios when PGA 0.35g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0184	0.4473	0.6939	0.8996	0.0467
4	0.0187	0.2719	0.7122	0.9210	0.0005
3	0.0180	0.3599	0.6699	0.8702	0.0137
2	0.0155	0.3995	0.5270	0.6805	0.0264
1	0.0084	0.3496	0.1972	0.1300	0.0111

Table 5.6: Damage Ratios when PGA 0.3g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0152	0.4093	0.5107	0.6573	0.0300
4	0.0155	0.2599	0.5270	0.6805	0.0005
3	0.0147	0.3271	0.4841	0.6183	0.0060
2	0.0127	0.3763	0.3828	0.4562	0.0185
1	0.0063	0.3075	0.1243	0.0396	0.0026

Table 5.7: Damage Ratios when PGA 0.25g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0111	0.3658	0.3084	0.3237	0.0154
4	0.0117	0.2306	0.3356	0.3730	0.0004
3	0.0114	0.2739	0.3219	0.3482	0.0005
2	0.0101	0.3209	0.2651	0.2448	0.0049
1	0.0054	0.2611	0.0971	0.0198	0.0005

Table 5.8: Damage Ratios when PGA 0.2g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0067	0.3129	0.1372	0.0520	0.0035
4	0.0075	0.2102	0.1645	0.0835	0.0002
3	0.0077	0.2313	0.1715	0.0929	0.0004
2	0.0069	0.2636	0.1439	0.0590	0.0005
1	0.0036	0.2140	0.0507	0.0044	0.0002

Table 5.9: Damage Ratios when PGA 0.15g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0037	0.2481	0.0529	0.0047	0.0004
4	0.0046	0.1752	0.0751	0.0099	0.0000
3	0.0050	0.1847	0.0858	0.0140	0.0000
2	0.0044	0.1960	0.0699	0.0083	0.0000
1	0.0022	0.1621	0.0230	0.0017	0.0000

Table 5.10: Damage Ratios when PGA 0.1g

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0016	0.1841	0.0138	0.0003	0.0000
4	0.0024	0.1333	0.0264	0.0021	0.0000
3	0.0026	0.1352	0.0301	0.0024	0.0000
2	0.0024	0.1354	0.0264	0.0021	0.0000
1	0.0012	0.1090	0.0087	0.0001	0.0000

Table 5.11: Damage Ratios when PGA 0.5g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0176	0.4674	0.6462	0.8403	0.0569
4	0.0200	0.3427	0.7932	1.0000	0.0094
3	0.0215	0.3834	0.8908	1.0000	0.0208
2	0.0208	0.4459	0.8448	1.0000	0.0460
1	0.0130	0.4535	0.3974	0.4811	0.0497

Table 5.12: Damage Ratios when PGA 0.45g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0144	0.4381	0.4683	0.5946	0.0423
4	0.0169	0.3209	0.6054	0.7874	0.0049
3	0.0184	0.3578	0.6939	0.8996	0.0131
2	0.0178	0.4133	0.6580	0.8553	0.0317
1	0.0109	0.4117	0.2996	0.3075	0.0310

Table 5.13: Damage Ratios when PGA 0.4g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0122	0.4086	0.3589	0.4146	0.0298
4	0.0147	0.3025	0.4841	0.6183	0.0018
3	0.0162	0.3314	0.5657	0.7341	0.0069
2	0.0157	0.3740	0.5380	0.6959	0.0178
1	0.0092	0.3693	0.2282	0.1802	0.0164

Table 5.14: Damage Ratios when PGA 0.35g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0100	0.3791	0.2609	0.2373	0.0194
4	0.0124	0.2864	0.3684	0.4313	0.0007
3	0.0139	0.3045	0.4425	0.5546	0.0021
2	0.0134	0.3337	0.4172	0.5140	0.0074
1	0.0077	0.3261	0.1715	0.0929	0.0058

Table 5.15: Damage Ratios when PGA 0.3g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0069	0.3477	0.1439	0.0590	0.0106
4	0.0090	0.2641	0.2203	0.1669	0.0005
3	0.0107	0.2769	0.2908	0.2915	0.0005
2	0.0105	0.2931	0.2821	0.2757	0.0008
1	0.0060	0.2817	0.1150	0.0318	0.0006

Table 5.16: Damage Ratios when PGA 0.25g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0045	0.3103	0.0725	0.0090	0.0030
4	0.0065	0.2381	0.1307	0.0455	0.0004
3	0.0084	0.2450	0.1972	0.1300	0.0004
2	0.0086	0.2547	0.2048	0.1418	0.0005
1	0.0051	0.2410	0.0886	0.0153	0.0004

Table 5.17: Damage Ratios when PGA 0.2g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0029	0.2612	0.0358	0.0029	0.0005
4	0.0046	0.2098	0.0751	0.0099	0.0002
3	0.0060	0.2117	0.1150	0.0318	0.0002
2	0.0062	0.2105	0.1212	0.0369	0.0002
1	0.0035	0.1966	0.0484	0.0041	0.0000

Table 5.18: Damage Ratios when PGA 0.15g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0017	0.2152	0.0152	0.0006	0.0002
4	0.0027	0.1741	0.0319	0.0026	0.0000
3	0.0037	0.1690	0.0529	0.0047	0.0000
2	0.0040	0.1637	0.0600	0.0059	0.0000
1	0.0022	0.1486	0.0230	0.0017	0.0000

Table 5.19: Damage Ratios when PGA 0.1g with Viscous Dampers

story	story drift ratio	story acceleration (in g)	structural damage ratio	nonstructur. damage ratio	contents damage ratio
5	0.0011	0.1611	0.0076	0.0000	0.0000
4	0.0017	0.1329	0.0152	0.0006	0.0000
3	0.0021	0.1261	0.0213	0.0015	0.0000
2	0.0023	0.1141	0.0247	0.0019	0.0000
1	0.0013	0.1003	0.0099	0.0000	0.0000

5.4 Comparison

The deformation comparisons of these two designs are presented in Figures 5.19 to 5.27. In these figures, the labels "ductile" and "damper" refer to the first and second options.

Damage ratio comparisons for structural and nonstructural damage in each story are presented in Figures 5.28 to 5.37.

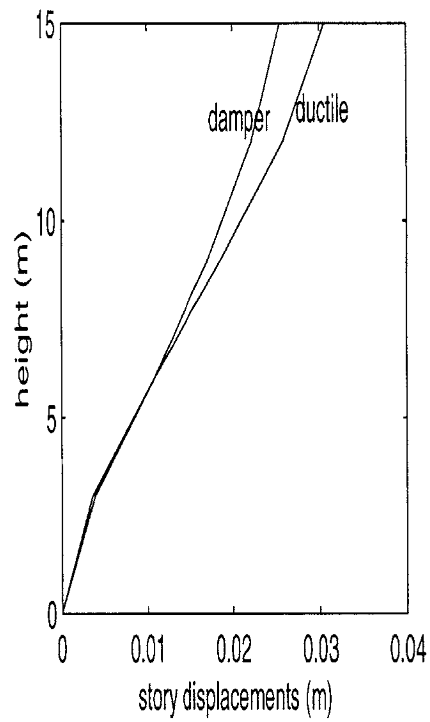

Figure 5.19: Comparison of Drifts when PGA 0.1g

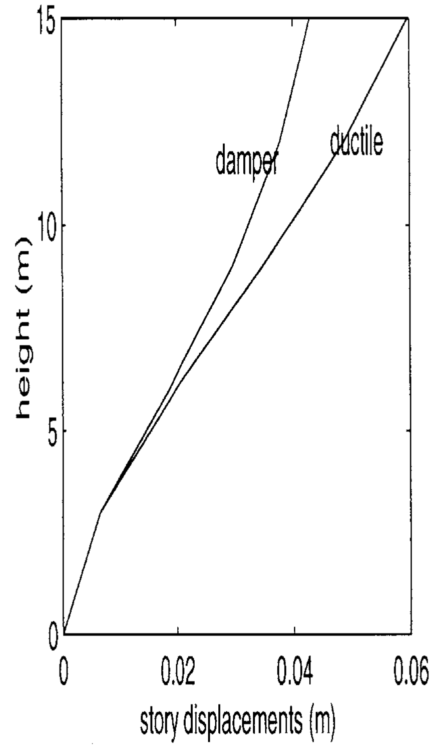

Figure 5.20: Comparison of Drifts when PGA 0.15g

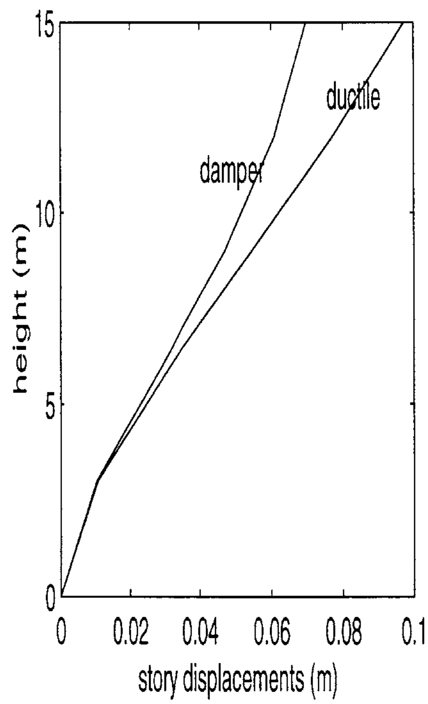

Figure 5.21: Comparison of Drifts when PGA 0.2g

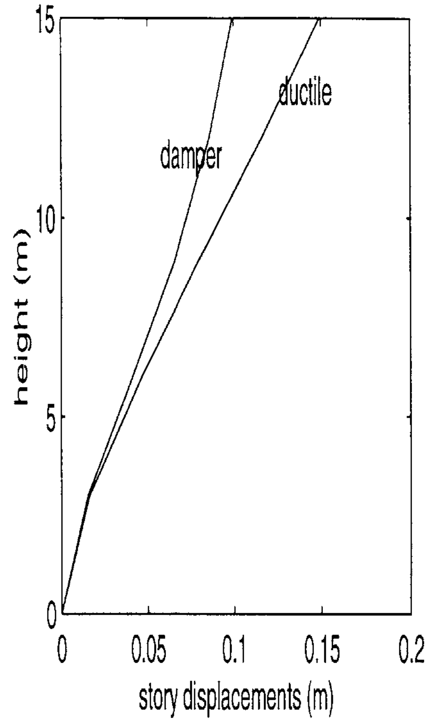

Figure 5.22: Comparison of Drifts when PGA 0.25g

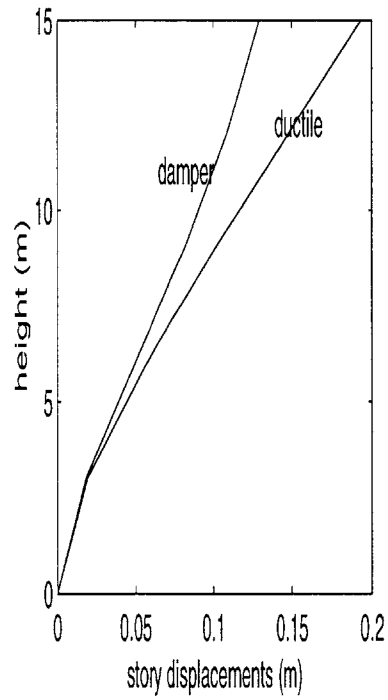

Figure 5.23: Comparison of Drifts when PGA 0.3g

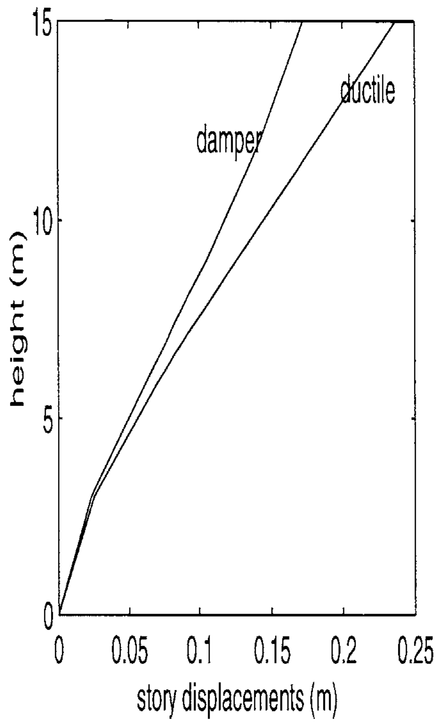

Figure 5.24: Comparison of Drifts when PGA 0.35g

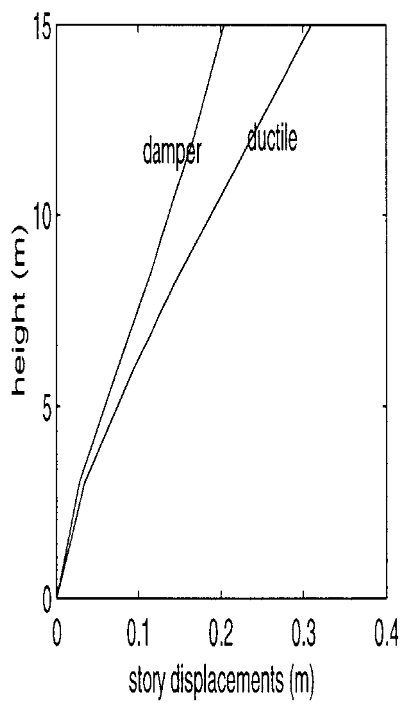

Figure 5.25: Comparison of Drifts when PGA 0.4g

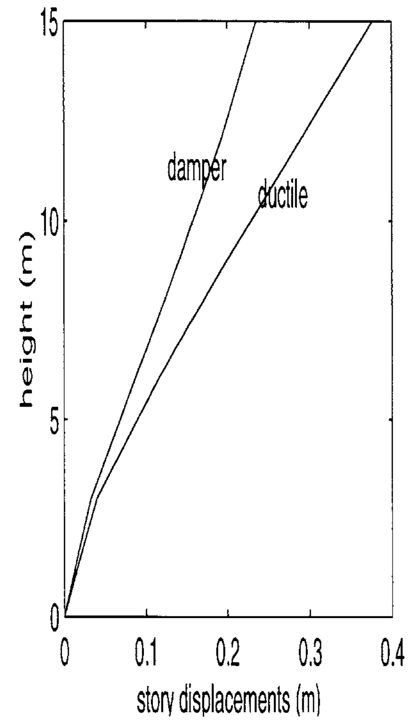

Figure 5.26: Comparison of Drifts when PGA 0.45g

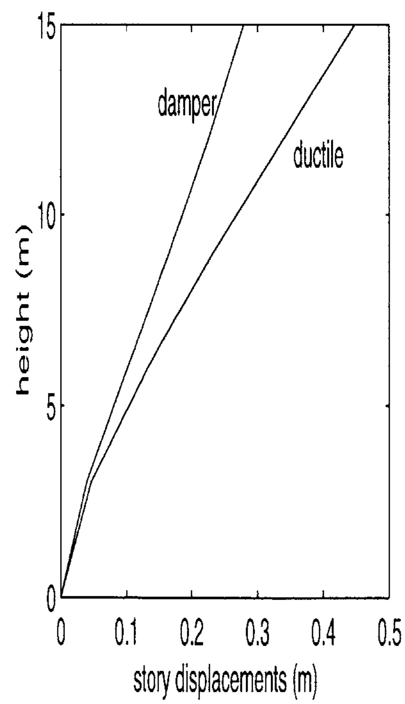

Figure 5.27: Comparison of Drifts when PGA 0.5g

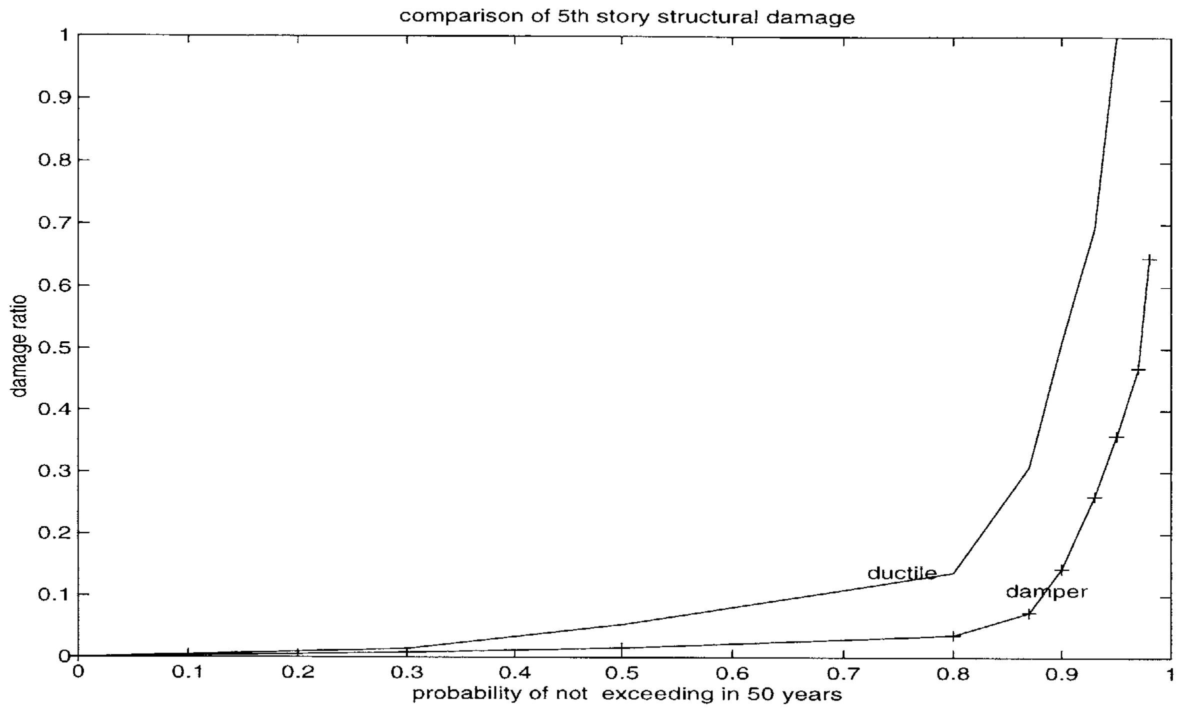

Figure 5.28: Comparison of 5th Story Structural Damage Ratios

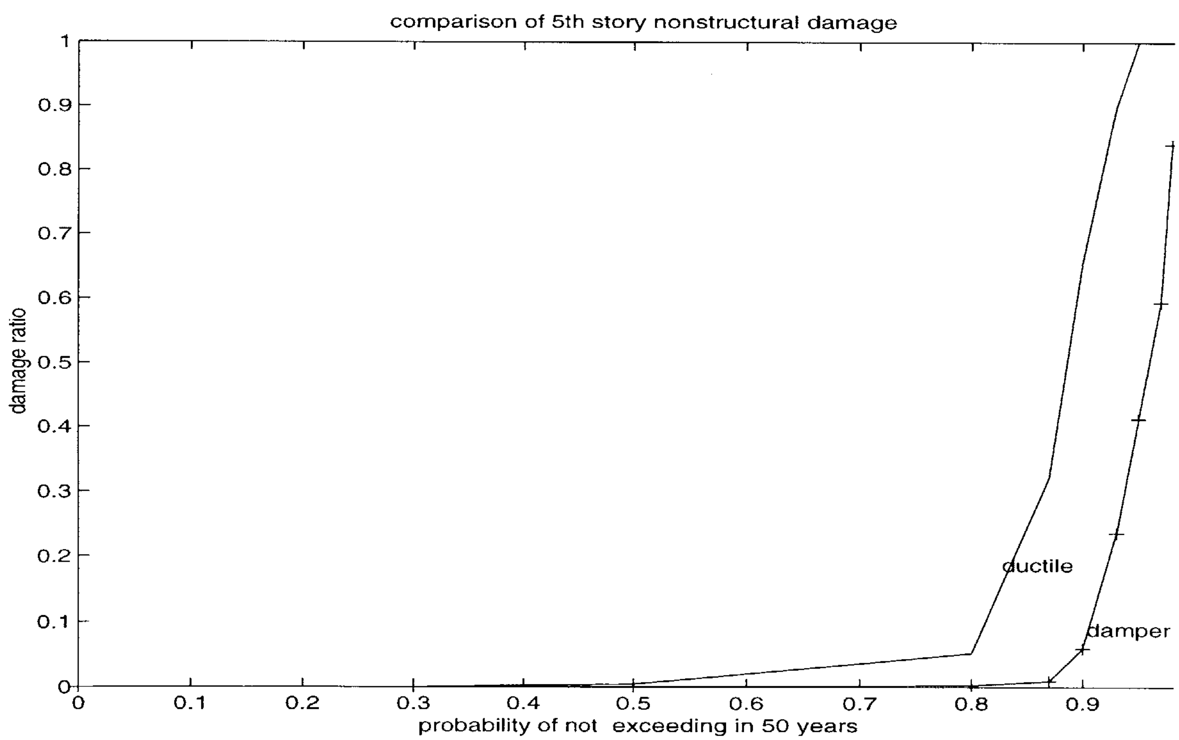

Figure 5.29: Comparison of 5th Story Nonstructural Damage Ratios

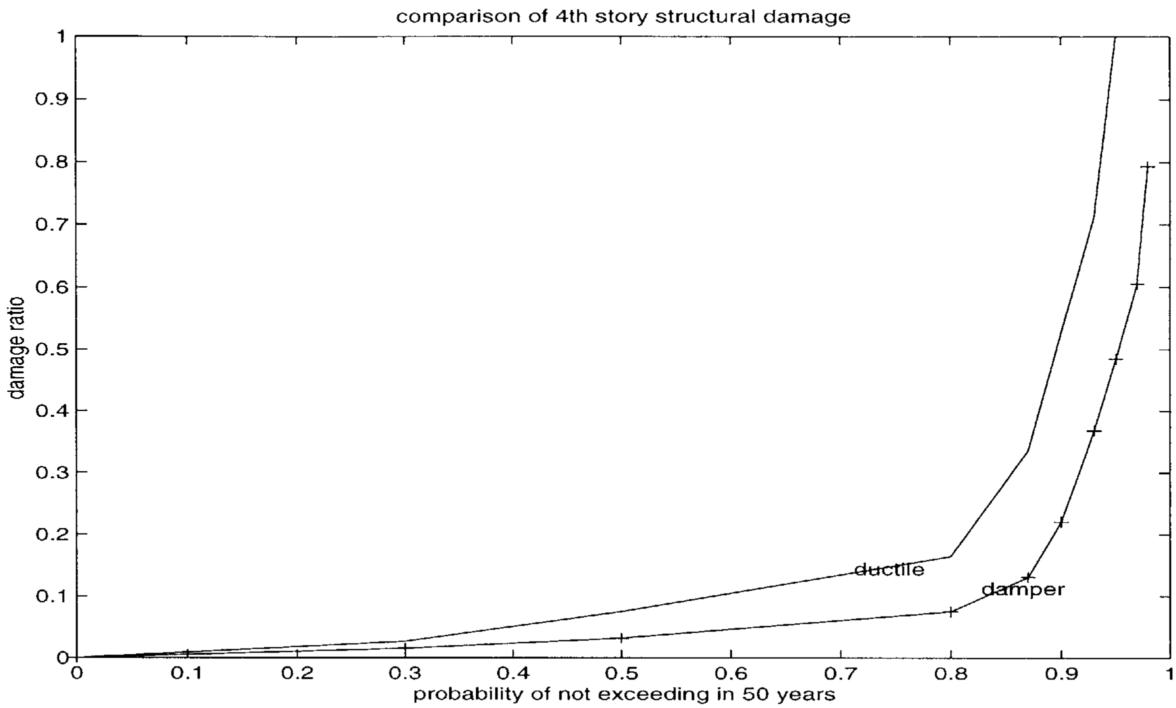

Figure 5.30: Comparison of 4th Story Structural Damage Ratios

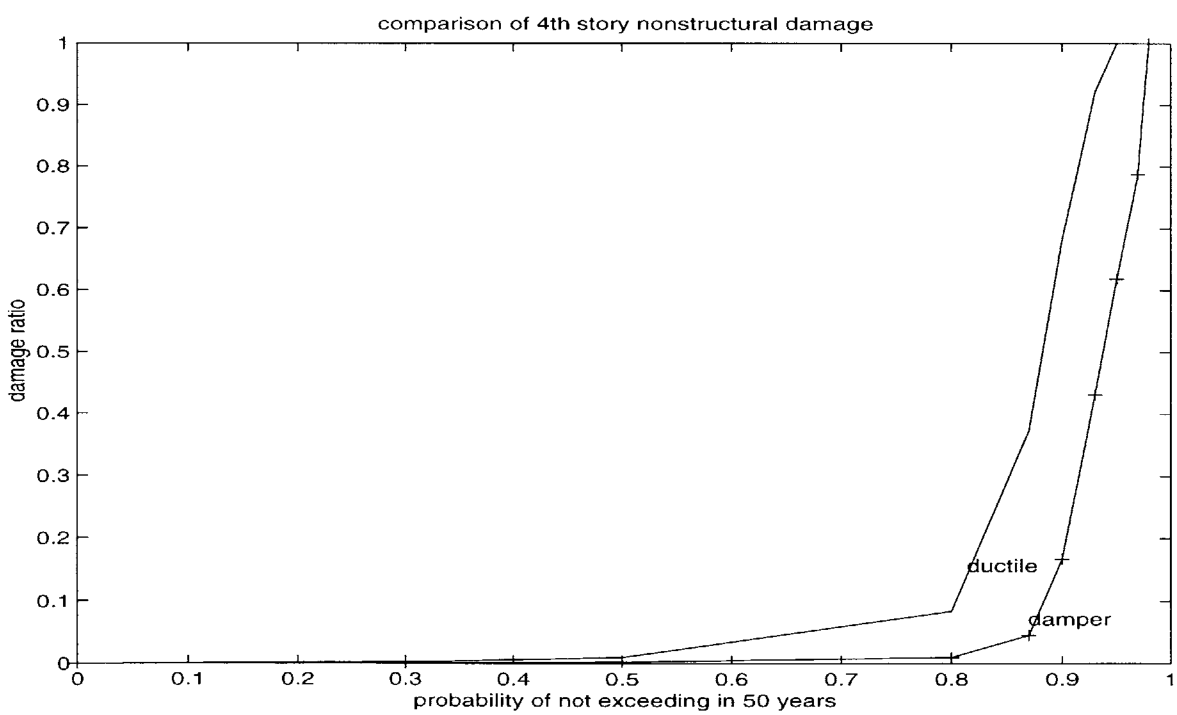

Figure 5.31: Comparison of 4th Story Nonstructural Damage Ratios

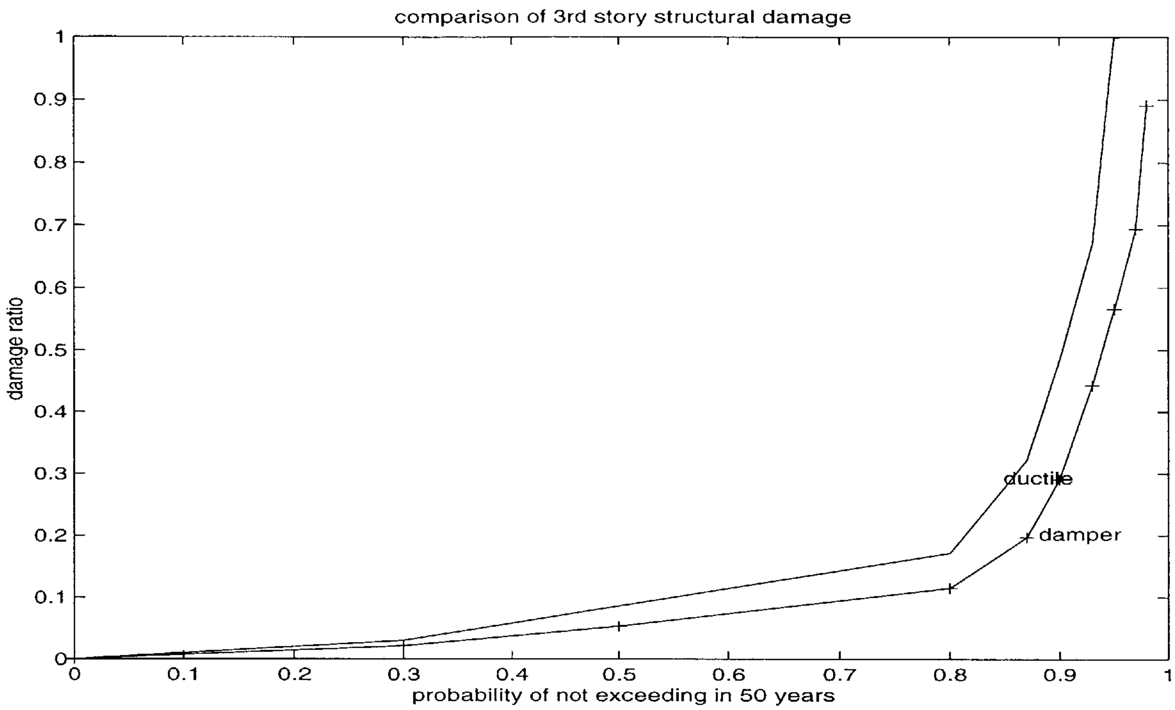

Figure 5.32: Comparison of 3rd Story Structural Damage Ratios

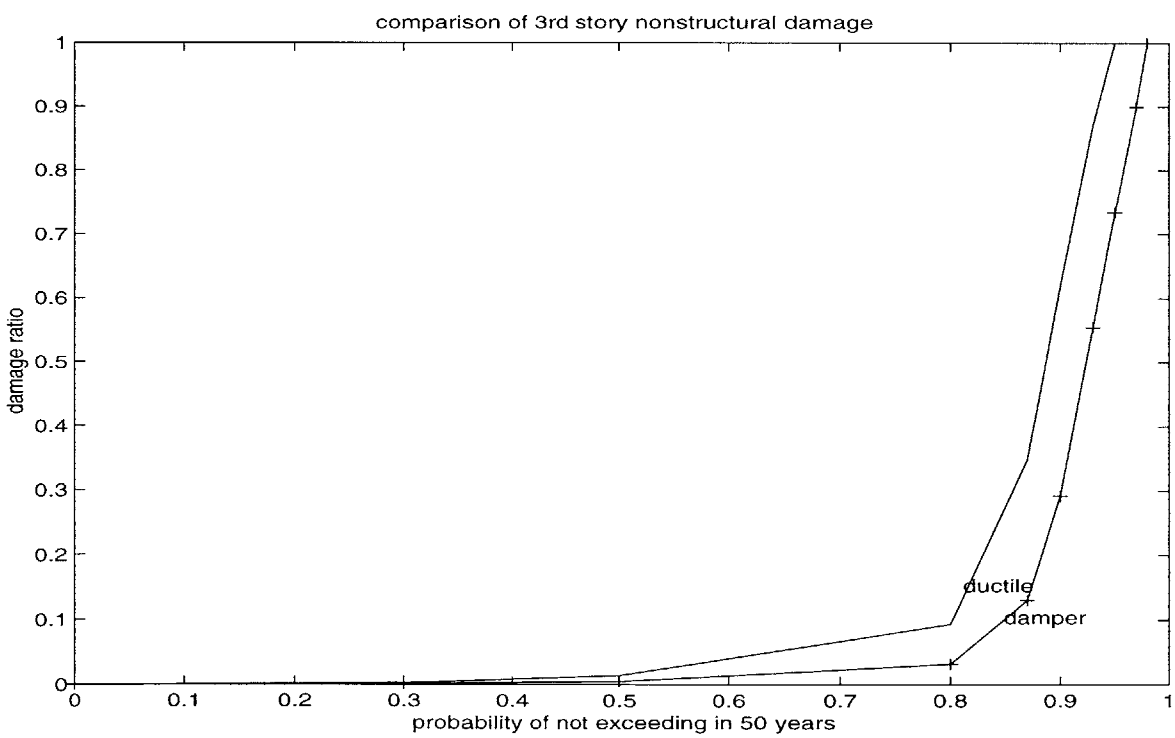

Figure 5.33: Comparison of 3rd Story Nonstructural Damage Ratios

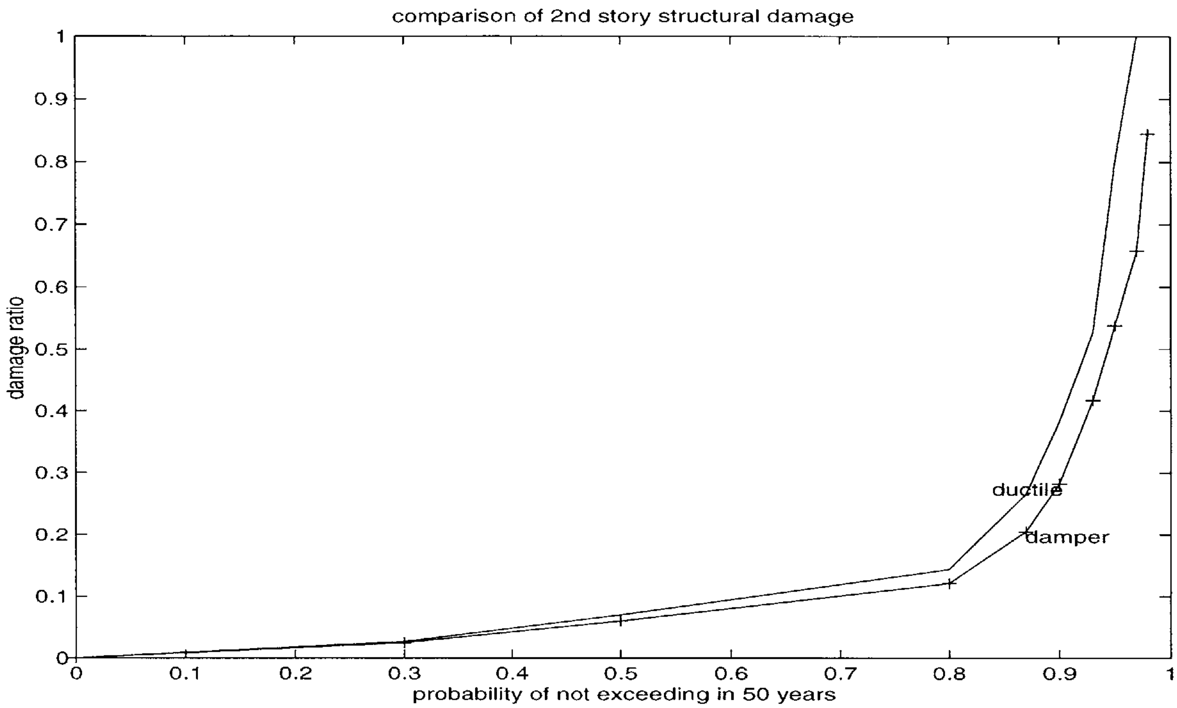

Figure 5.34: Comparison of 2^{nd} Story Structural Damage Ratios

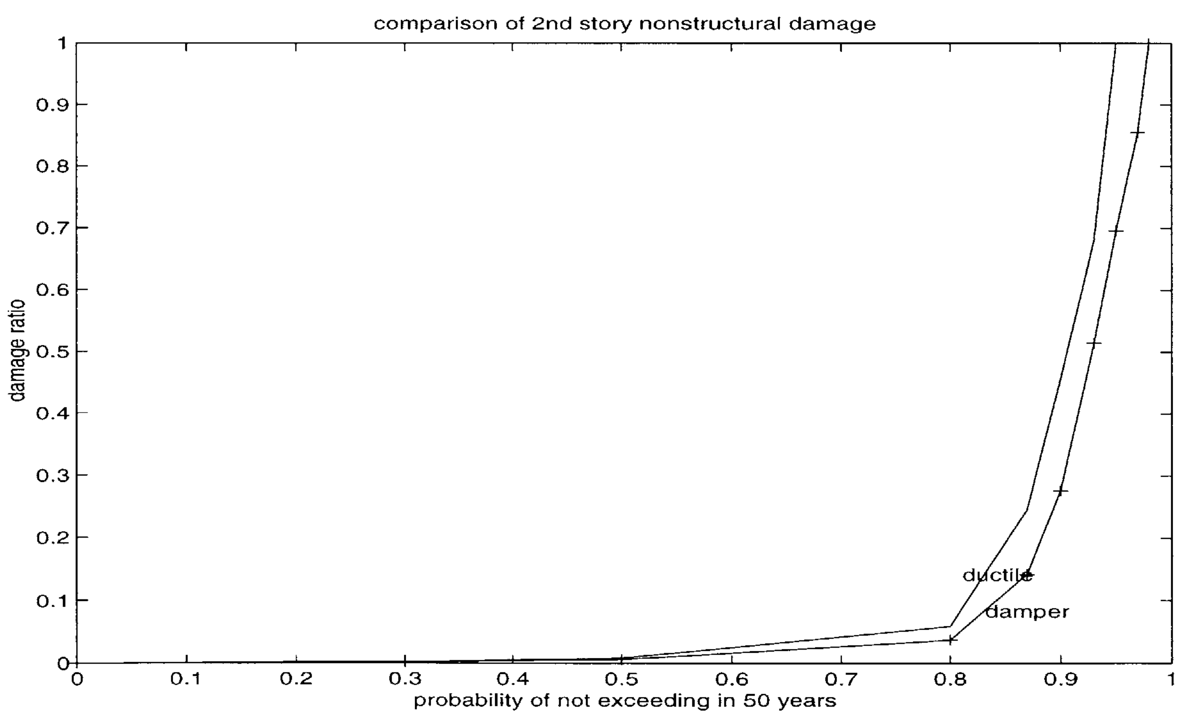

Figure 5.35: Comparison of 2^{nd} Story Nonstructural Damage Ratios

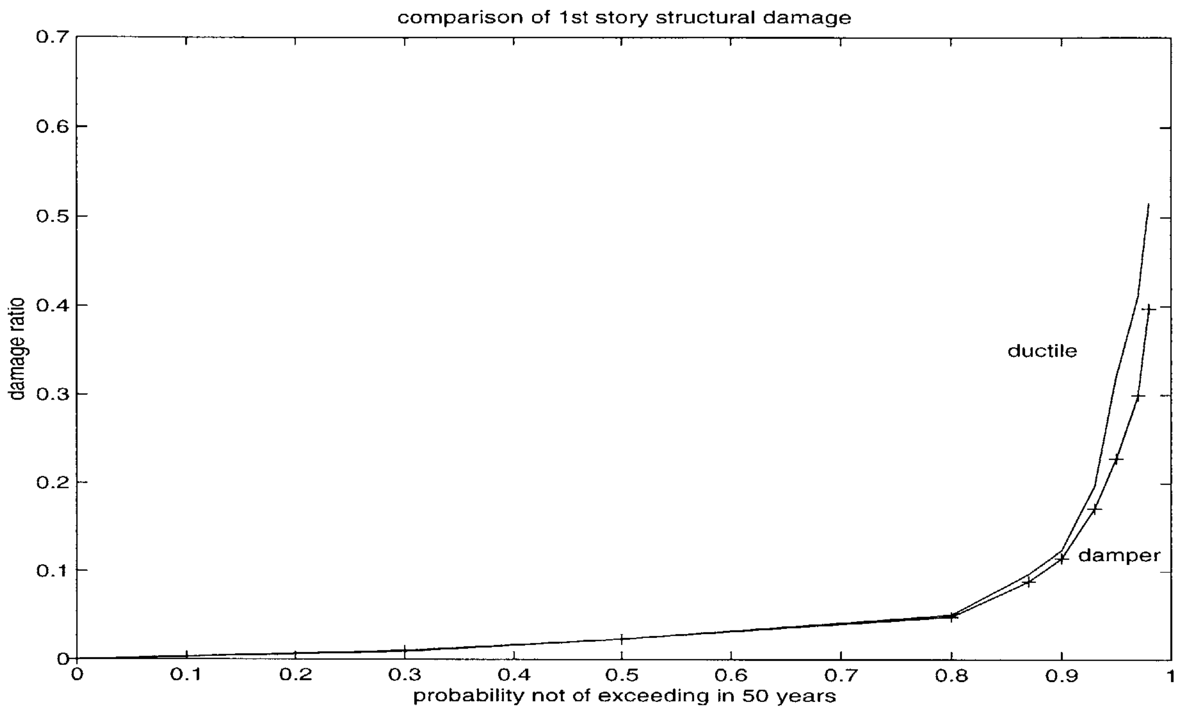

Figure 5.36: Comparison of 1st Story Structural Damage Ratios

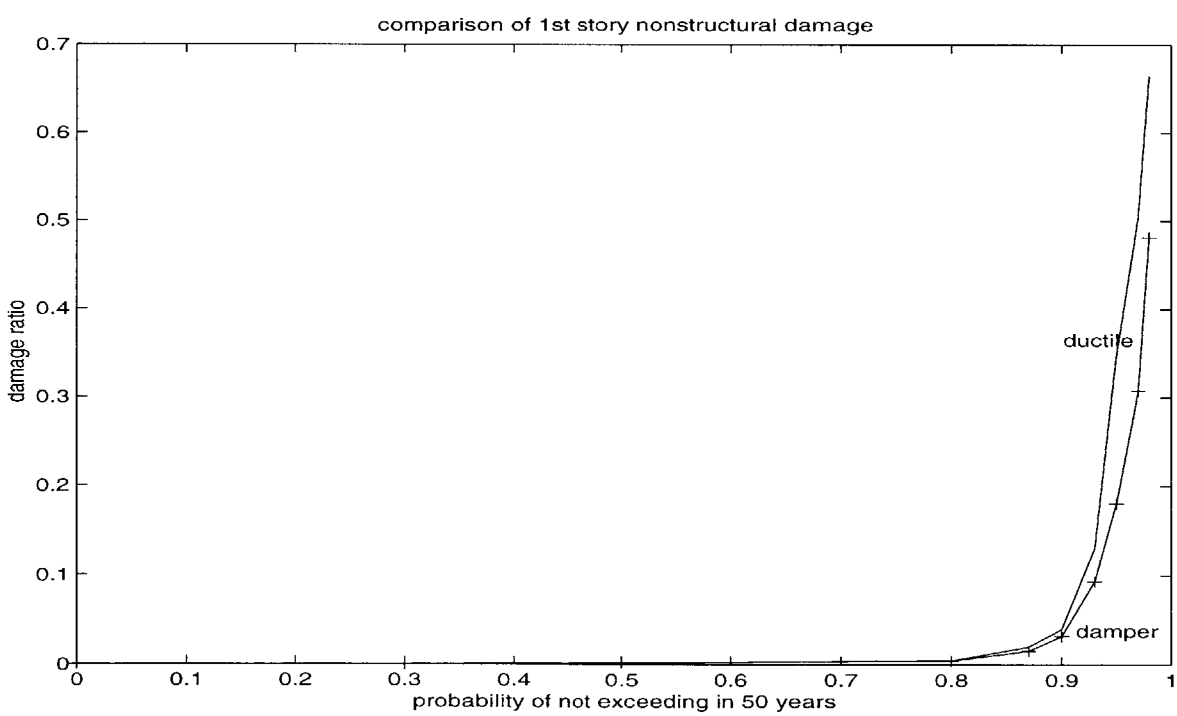

Figure 5.37: Comparison of 1st Story Nonstructural Damage Ratios

The overall structural and nonstructural damage ratios are also found from the story damage ratios by using weighting factors. They are presented in Figure 5.38 and 5.39, respectively.

$$OverallDR = \frac{\sum_{1}^{n} w_i DR_i}{\sum_{1}^{n} w_i} \tag{5.1}$$

where

w_i - weighting factor for the i^{th} story

DR_i - damage ratio for the i^{th} story

n - number of stories

Since we are interested in monetary values, the weighting factor is taken to be the cost. For the structural damage ratio, the weighting factor of each story is the initial structural cost of each story. For nonstructural damage ratio, the weighting factor of each story is the initial nonstructural cost of each story.

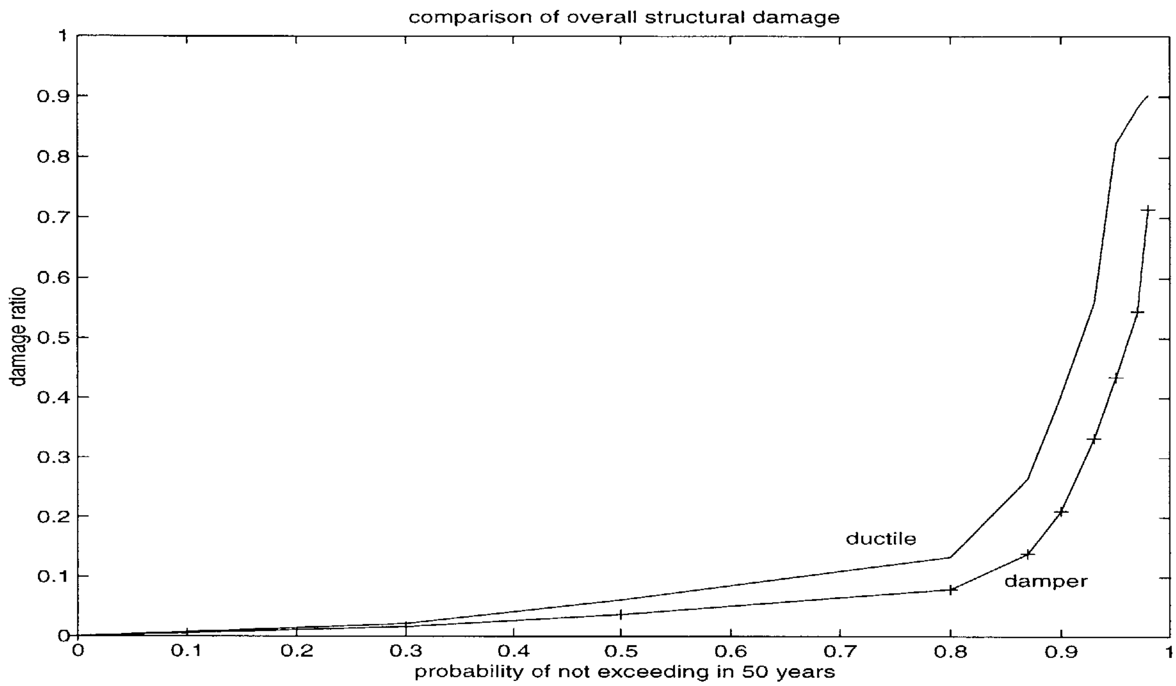

Figure 5.38: Comparison of Overall Structural Damage

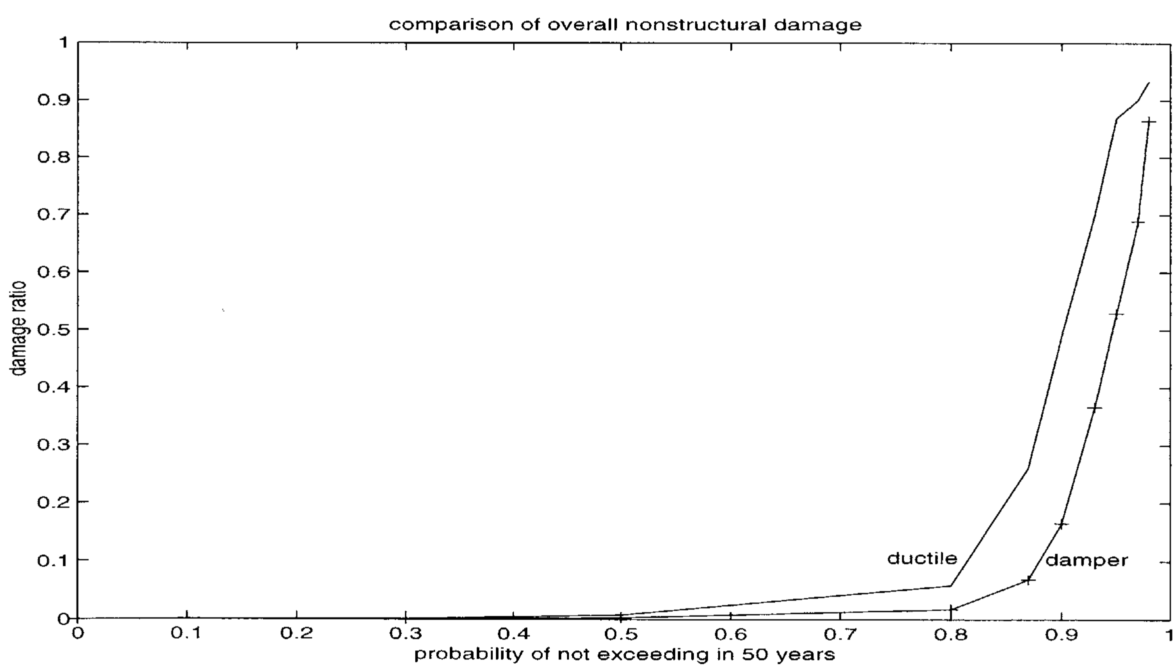

Figure 5.39: Comparison of Overall Nonstructural Damage

A cost comparison between the design options is also undertaken. The structural cost of the two designs is calculated first. For the calculation of the cost, the price used for concrete is \$98 per m^3, the price for steel is \$0.26 per pound, and the price for a 150 k damper is \$7000.

Several cost-benefit analyses are carried out where, in each case, the structural and content costs are the same but the nonstructural cost is varied so that several initial costs can be used. As the initial cost of the investment on the building increases, the added protection becomes more attractive. If the building is not of great value, unless the business interruption is not very important to the owner, he/she probably wouldn't like to spend money on the protection of the building, which could be as high as the building's initial cost. But as the initial cost of the building increases, the money spent on the protection becomes more beneficial to the owner. This trend is shown in Figures 5.38 to 5.42

name	cost (\$)	percentage of initial (%)
initial str. cost (ductile)	142062.1	24.7
initial nonstr. cost (ductile)	289385.8	50.6
initial content cost (ductile)	142062.1	24.7
initial cost (ductile)	573510	100
initial str. cost (damper)	146095	24.7
initial nonstr. cost (damper)	297600.9	50.6
initial cont. cost (damper)	146095	24.7
initial c. without dampers	589790.9	100
damper cost	140000	23.7
initial cost with dampers	729790.9	123.7

Table 5.20: Cost Data for the 1st Cost Assumption

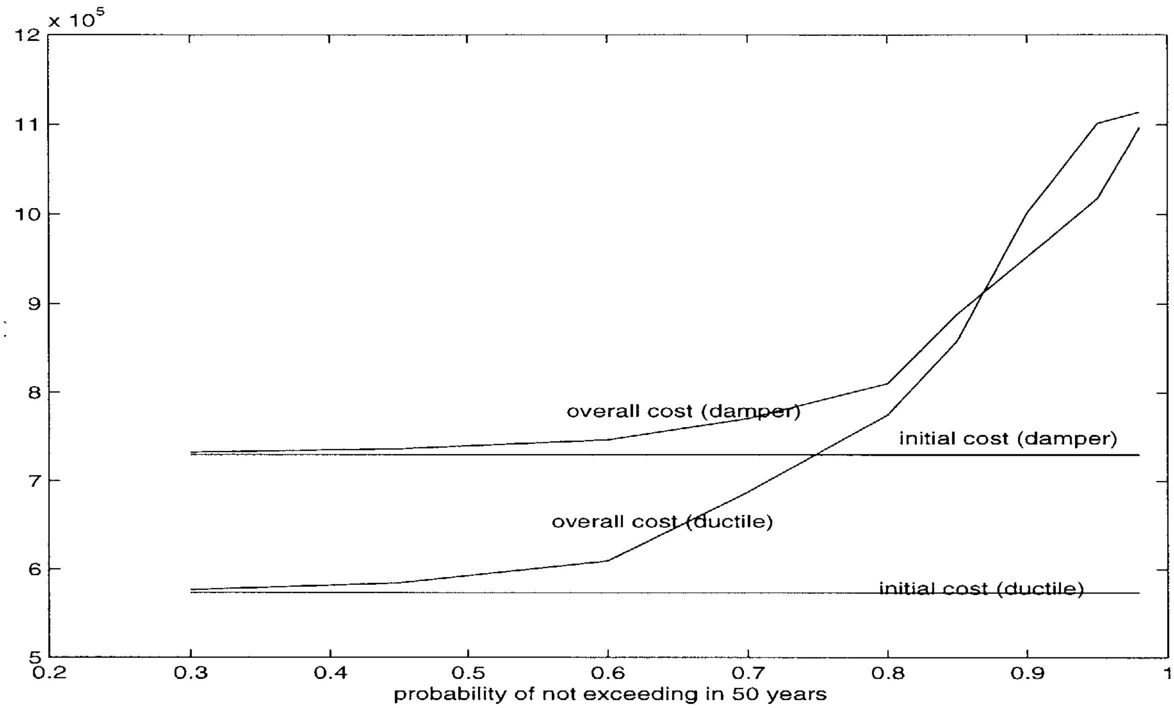

Figure 5.40: Cost Comparison between two Design Options for the 1st Cost Assumption

name	cost ($)	percentage of initial (%)
initial str. cost (ductile)	142062.1	14.3
initial nonstr. cost (ductile)	710026.2	71.4
initial content cost (ductile)	142062.1	14.3
initial cost (ductile)	994434.4	100
initial str. cost (damper)	146095	14.3
initial nonstr. cost (damper)	730475	71.4
initial cont. cost (damper)	146095	14.3
initial c. without dampers	1022665	100
damper cost	140000	13.7
initial cost with dampers	1162665	113.7

Table 5.21: Cost Data for the 2nd Cost Assumption

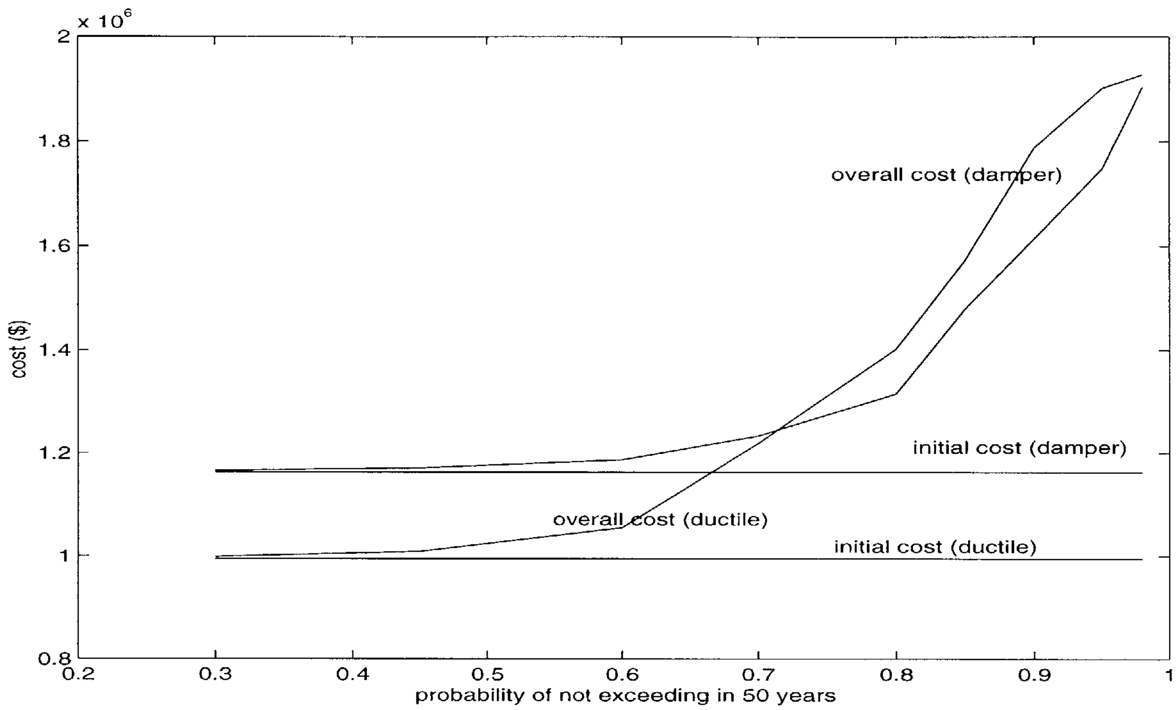

Figure 5.41: Cost Comparison between two Design Options for the 2nd Cost Assumption

name	cost ($)	percentage of initial (%)
initial str. cost (ductile)	142062.1	9.1
initial nonstr. cost (ductile)	1278274.8	81.8
initial content cost (ductile)	142062.1	9.1
initial cost (ductile)	1562683	100
initial str. cost (damper)	146095	9.1
initial nonstr. cost (damper)	1314855	81.8
initial cont. cost (damper)	146095	9.1
initial c. without dampers	1607045	100
damper cost	140000	8.7
initial cost with dampers	1747045	108.7

Table 5.22: Cost Data for the 3rd Cost Assumption

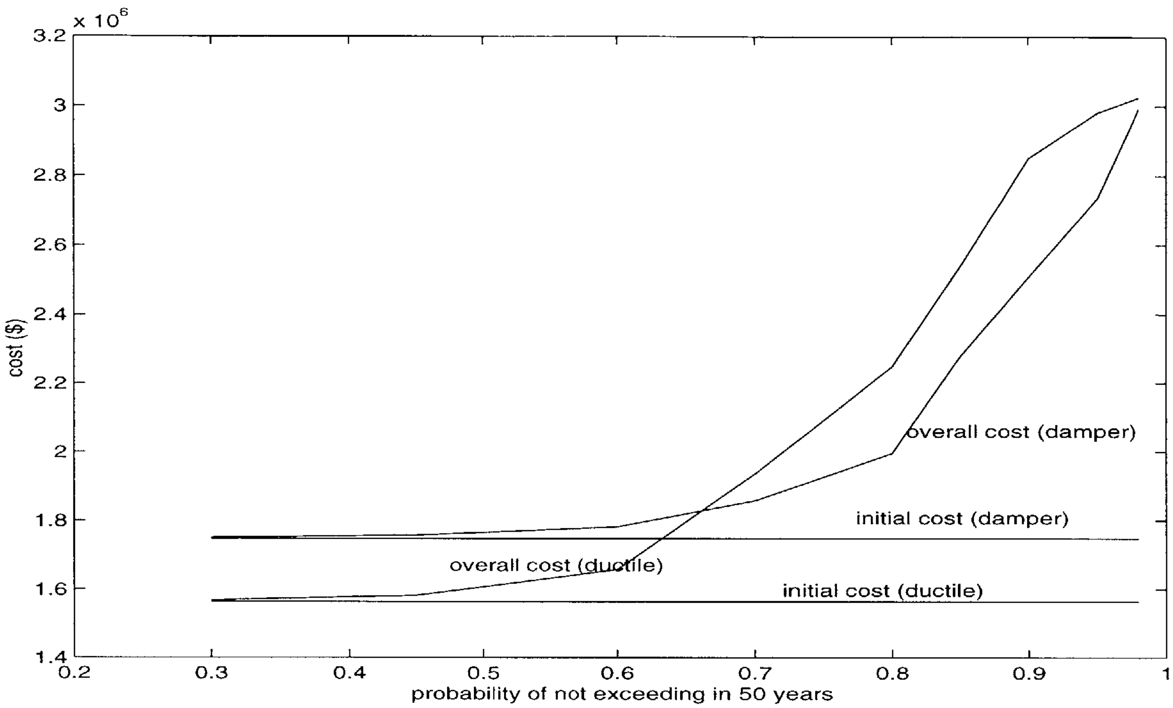

Figure 5.42: Cost Comparison between two Design Options for the 3rd Cost Assumption

name	cost ($)	percentage of initial (%)
initial str. cost (ductile)	142062.1	5
initial nonstr. cost (ductile)	2557116.8	90
initial content cost (ductile)	142062.1	5
initial cost (ductile)	2841241	100
initial str. cost (damper)	146095	5
initial nonstr. cost (damper)	2619710	90
initial cont. cost (damper)	146095	5
initial c without dampers	2911900	100
damper cost	140000	4.8
initial cost with dampers	3061900	104.8

Table 5.23: Cost Data for the 4th Cost Assumption

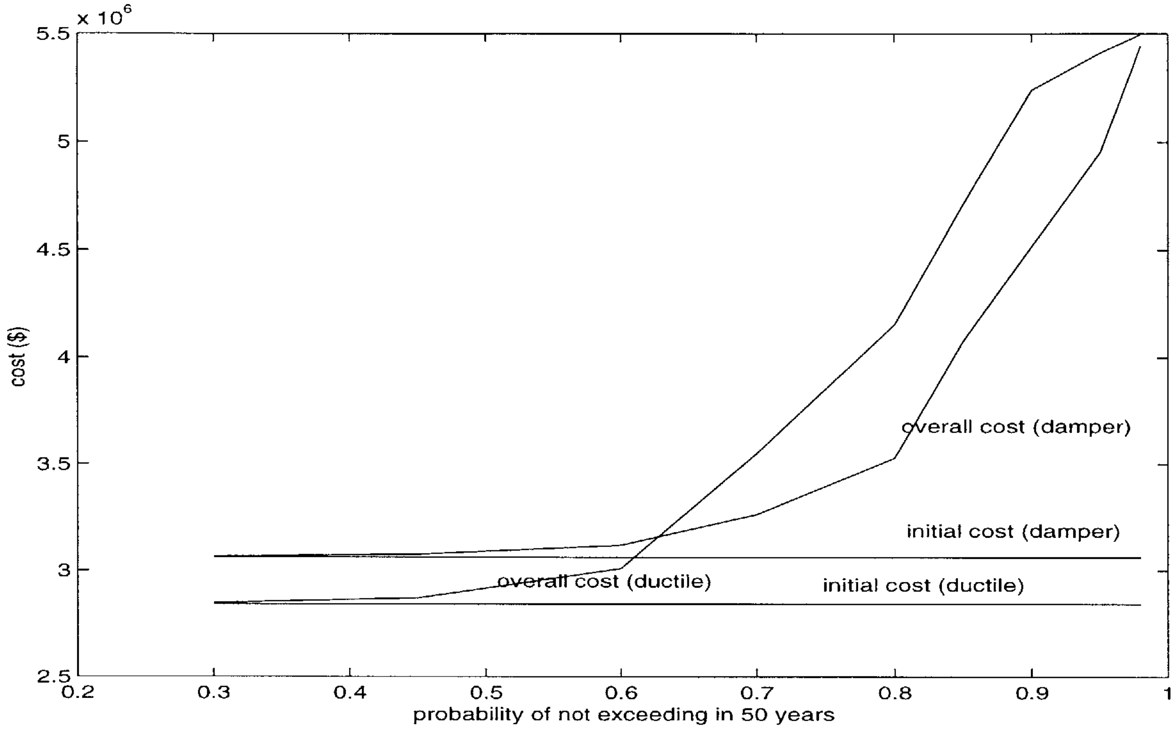

Figure 5.43: Cost Comparison between two Design Options for the 4th Cost Assumption

name	cost ($)	percentage of initial (%)
initial str. cost (ductile)	142062.1	3.7
initial nonstr.cost (ductile)	3551550.8	92.6
initial content cost (ductile)	142062.1	3.7
initial cost (ductile)	3835675	100
initial str. cost (damper)	146095	3.7
initial nonstr. cost (damper)	3652374	92.6
initial cont. cost (damper)	146095	3.7
initial c. without dampers	3944564	100
damper cost	140000	3.5
initial cost with dampers	4084564	103.5

Table 5.24: Cost Data for the 5th Cost Assumption

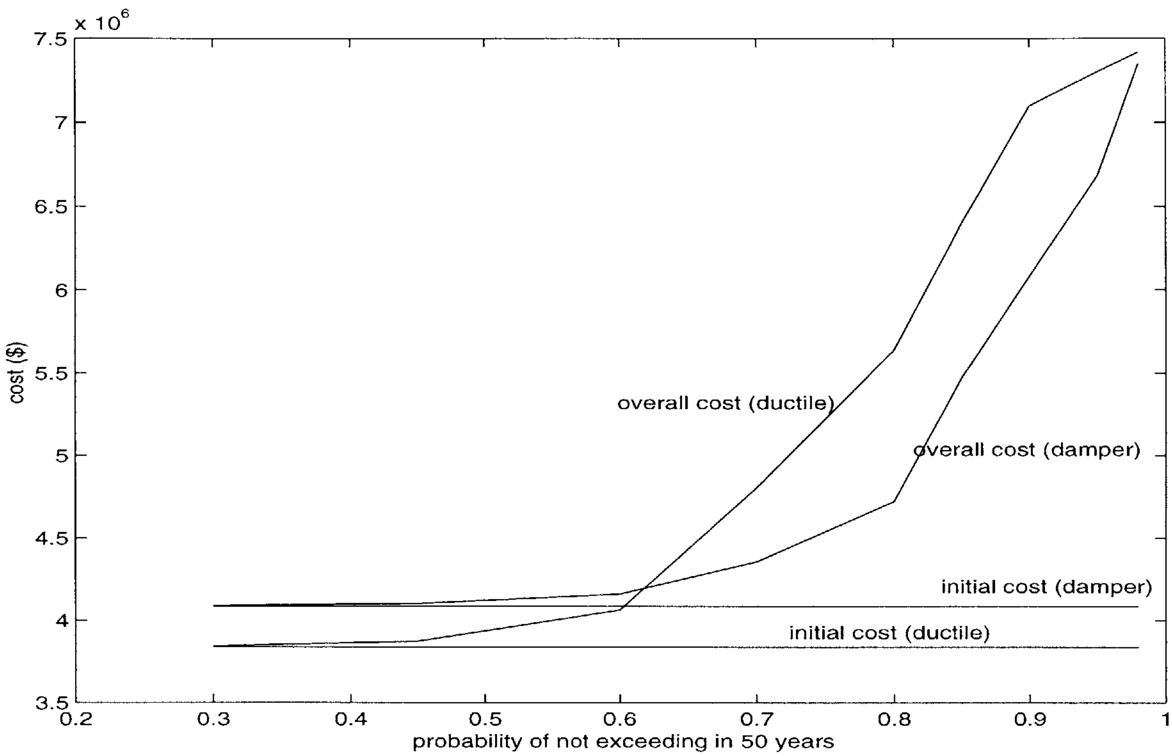

Figure 5.44: Cost Comparison between two Design Options for the 5th Cost Assumption

The benefit of added protection can also be seen by examining the Figure 5.45, where

$$DIFR = \frac{inital\cos t_2 - initial\cos t_1}{repair\cos t_1 - repair\cos t_2} \tag{5.2}$$

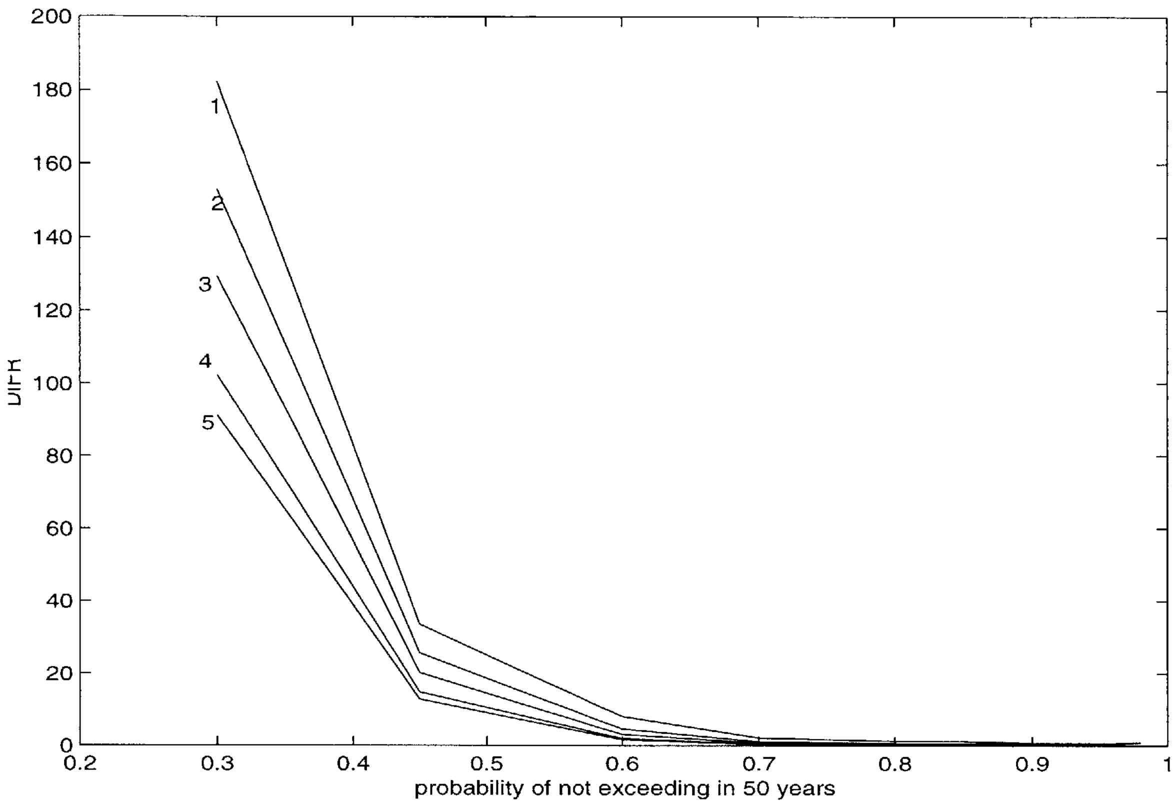

Figure 5.45: DIFR vs. probability of not exceeding in 50 years Curves for each Cost Assumption

Chapter 6

Conclusion

6.1 Concluding Remarks

A review of economic consequences of recent earthquakes calls a change for the earthquake resistant design philosophy. For many years the codes' approach was to meet life-safety criterion. Now it is obvious that we need more clearly defined criterion which also considers economy. The goal is to change the design process that does not inform the owner about the expected performance to another design philosophy where the owner is aware of his/her choices.

Damage controlled design will hopefully be the new design approach of future seismic codes. By defining various performance levels, it controls property and business interruption damage after an earthquake. Each day more and more companies in industry are applying this methodology to their design to satisfy their clients.

In this thesis, an application of damage controlled design is presented. The importance of consideration of overall cost, which includes the repair cost after a seismic event, in making rational design decisions is displayed. With modern seismic design tools, the structural response and, as a result of it, damage to a structure and to its components during an earthquake can be reduced. The benefit of using modern seismic design tools is revealed.

We suggest that if the engineer is able to show the owner what he/she buys for which level of performance, the owner can make his/her decision more easily and knows what he/she is paying for.

In our calculations, we didn't take business interruption into account which can actually be, dependent on the usage of the building, owner's main concern by defining the performance objectives. While presenting the owner his/her options this fact should also be reminded.

References

[1] I.D. Aiken, J.M. Kelly. Seismic Isolation - A Case Study of Research into Practice in the Field of Earthquake Engineering. *Proceedings of Research Transformed into Practice: Implementation of NSF Research*, pages 520-528, Arlington, VA, 1995.

[2] I.D. Aiken, J.M. Kelly, P. Mahmoodi. The Application of Viscoelastic Dampers to Seismically Resistant Structures. *Proceedings of Fourth National Conference on Earthquake Engineering,* 3, pages 459-468, Earthquake Engineering REsearch Institute, Oakland, California, 1990.

[3] E. Booth. *Concrete Structures in Earthquake Regions: Design and Analysis.* Longman Scientific & Technical, 1994

[4] E. Booth. Earthquake Engineering in 1990s: achievements, concerns, and future directions. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 128(2), pages 154-166, May 1998

[5] K.C. Chang, T.T. Soong, M.L. Lai and E.J. Nielsen. Viscoelastic Dampers as Energy Dissipation Devices for Structural Applications. *Earthquake Spectra*, 9(3), pages 371-387, 1993.

[6] K.C. Chang, T.T. Soong, S-T. Oh, M.L. Lai. Effect of Ambient Temperature on Viscoelastically Damped Structure. *Journal of Structural Engineering*, ASCE, 118(7), pages 1955-1973, 1992.

[7] S. Cherry, A. Filiatrault. Seismic Response Control of Buildings Using Friction Dampers. *Earthquake Spectra*, 9(3), pages 447-466, 1993.

[8] D.J. Dowrick. *Earthquake Resistant Design,* John Willey, 1990.

[9] E.A. Fierro, C.L. Perry, H. Sedarat, and R.E. Scholl. Earthquake Dampers Used for Seismic Retrofit of Building in San Francisco. *Proceedings of Structures Congress '93,* pages 754-759, Irvine, CA, 1993.

[10] E.L. Garcia. Economic Considerations of Displacement-Based Seismic Design of Structural Concrete Buildings. *Structural Engineering International*, 6(4), pages 243-248, 1996.

[11] S.K.V. Gunturi, H.C. Shah. Building specific damage estimation. *Proceedings of the Tenth World Conference on Earthquake Engineering,* Vol. 10, pages 6001-6008, Rotterdam, 1992.

[12] T. K. Hasselman, J.H. Wiggins. Earthquake Damage to High-Rise Buildings as a Function of Interstory Drift. *Proceedings of Third International Earthquake Microzonation Conference*, University of Washington Seattle1982vol.2, pages 883-894, 1982.

[13] http://smdb.crustal.ucsb.edu/ows-bin/owa/summary1.main

[14] http://www.eqe.com

[15] http://www.taylordevices.com

[16] ICBO. *UBC:97 Uniform Building Code,* International Conference of Building Officials, Whittier, California, 1997

[17] H. Iemura. Active and Hybrid Control Development in Japan-Experiments and Implementetion.*Passive and Active Structural Vibration Control in Civil Engineering,* pages 355-371. Springer-Verlag, 1994

[18] *Journal of Engineering Mechanics*, 123(9), Sept. 1997.

[19] H.J. Lagorio. *Earthquakes An Architect's Guide to Nonstructural Seismic Hazards.* John Willey, 1990

[20] R.E. Lobo, J.M. Bracci, K.L. Shen, A.M. Reinhorn, T.T. Soong. Inelastic Response of R/C Structures with Viscoelastic Braces. *Earthquake Spectra,* 9(3), pages 419-446, 1993.

[21] *Loma Prieta Collection*, Earthquake Engineering Research Center, University of California, Berkeley.

[22] Y.J. Park, A.H.-S. Ang. Mechanistic Seismic Damage Model for Reinforced Concrete. *Journal of Structural Engineering*, ASCE, 111(4), pages 722-739, 1985.

[23] Y.J. Park, A.H.-S. Ang,Y.K. Wen. Damage-limiting Aseismic Design of Buildings.*Earthquake Spectra*, 3(1), pages 1-26, 1987.

[24] G.G. Penelis. A Statistical Evaluation of Damage to Buildings in the Thessaloniki, Greece Earthquake of June 20, 1978. *Proceedings of Ninth World Conference on Earthquake Engineering,* Tokyo, Japan, Vol. 7, pages 187-192, 1978.

[25] H.C. Shah, M. Movassate. Seismic Risk Analysis - California State Water Project. *Proceedings of Fifth European Conference on Earthquake Engineering,* Ankara, Turkey, Vol 2, Paper No. 156, 1975.

[26] R.L. Sharpe. Acceptable Earthquake Damage or Desired Performance. *Proceedings of the Tenth World Conference on Earthquake Engineering,* Vol. 10, pages 5891-5895, Rotterdam, 1992.

[27] *Steinbrugge Collection*, Earthquake Engineering Research Center, University of California, Berkeley.

[28] Structural Engineers Association of California (SEAOC), Vision 2000 Committee. *Performance Based Seismic Engineering of Buildings*, 1995.

[29] T.T. Soong. Active Control Experiments and Structural Testing. *Passive and Active Structural Vibration Control in Civil Engineering*, pages 319-344. Springer-Verlag, 1994

[30] N. Taly. The Whittier Narrows, California Earthquake of October 1, 1987 - Performance of Buildings at California State University, Los Angeles. *Earthquake Spectra*, 4(2), pages 277-317, 1988.

[31] H. Tiedeman. A Statistical Evaluation of the Importance of Nonstructural Damage to Buildings. *Proceedings of Seventh World Conference on Earthquake Engineering*, Istanbul, Turkey, Vol. 6, pages 617-624, 1980.

[32] R.E. Valles, A.M. Reinhorn, S.K. Kunnath, C. Li, and A. Madan. *IDARC2D Version 4.0: A Computer Program for the Inelastic Damage Analysis of Buildings.* Technical Report NCEER-96-0010, NY, 1996.

[33] R.H. Zhang, T.T. Soong, P. Mahmoodi. Seismic Response of Steel Frame Structures. *Earthquake Engineering and Structural Dynamics*, 18(3), pages 389-396,1989.

Appendix A

IDARC Files

A.1 Input File

```
DAMPER
CONTROL DATA
5,1,1,1,0,1,1
ELEMENT TYPES
20,15,0,0,0,0,1,0,0,0
ELEMENT DATA
20,15,0,0,0,0,0,5,0
UNITS SYSTEM:KN-MM
2
FLOOR ELEVATIONS
3000.0,6000.0,9000.0,12000.0,15000.0
DESCRIPTION OF IDENTICAL FRAMES
1
PLAN CONFIGURATION
4
NODAL WEIGHTS
1,1,110.0,110.0,110.0,110.0
2,1,110.0,110.0,110.0,110.0
3,1,110.0,110.0,110.0,110.0
4,1,110.0,110.0,110.0,110.0
5,1,110.0,110.0,110.0,110.0
CODE FOR SPECITICATION OF USER PROPERTIES
0
CONCRETE PROPERTIES
1,0.0276,0.0,0.0,0.0,0.0,0.0
REINFORCEMENT PROPERTIES
1,0.4,0.0,0.0,0.0,0.0
HYSTERETIC MODELING RULES
2
1,2.0,0.00,0.1,1.0
2,2.0,0.00,0.1,1.0
MOMENT CURVATURE ENVELOPE GENERATION
0
COLUMN DIMENSIONS
1
1,1,1,137.5,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
2,1,1,275.0,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
3,1,1,275.0,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
4,1,1,137.5,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
```

```
1
5,1,1,137.5,3000.0,200.0,200.0
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1
6,1,1,275.0,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
7,1,1,275.0,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
8,1,1,137.5,3000.0,200.0,200.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
9,1,1,137.5,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
10,1,1,275.0,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
11,1,1,275.0,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
12,1,1,137.5,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
13,1,1,137.5,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
14,1,1,275.0,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
15,1,1,275.0,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
16,1,1,137.5,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
17,1,1,137.5,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
1
18,1,1,275.0,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
19,1,1,275.0,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,2640.0,10.0,200.0,0.5
1
20,1,1,137.5,3000.0,225.0,225.0
 -1,400.0,400.0,40.0,1920.0,10.0,200.0,0.5
BEAM MOMENT CURVATURE ENVELOPE GENERATION
0
BEAM DIMENSIONS
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  -2,400.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,230.0
2,1,1,6000.0,200.0,200.0
  -2,400.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,230.0
3,1,1,6000.0,200.0,200.0
```

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 -2,400.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,230.0
4,1,1,6000.0,200.0,200.0
 -2,400.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,230.0
5,1,1,6000.0,200.0,200.0
 -2,400.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,230.0
6,1,1,6000.0,200.0,200.0
 -2,400.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,230.0
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 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
9,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
10,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
11,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
12,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
13,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
14,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
15,1,1,6000.0,200.0,200.0
 -2,450.0,300.0,300.0,0.0,30.0,550.0,2200.0,10.0,250.0
V BRACE PROP
0,0
1,0.18,148.3,1.0
COLUMN CONNECTIVITY
1,1,1,1,4,5
2,2,1,2,4,5
3,3,1,3,4,5
4,4,1,4,4,5
5,5,1,1,3,4
6,6,1,2,3,4
7,7,1,3,3,4
8,8,1,4,3,4
9,9,1,1,2,3
10,10,1,2,2,3
11,11,1,3,2,3
12,12,1,4,2,3
13,13,1,1,1,2
14,14,1,2,1,2
15,15,1,3,1,2
16,16,1,4,1,2
17,17,1,1,0,1
18,18,1,2,0,1
19,19,1,3,0,1
20,20,1,4,0,1
BEAM CONNECTIVITY
1,1,5,1,1,2
2,2,5,1,2,3
3,3,5,1,3,4
4,4,4,1,1,2
5,5,4,1,2,3
6,6,4,1,3,4
```

```
7,7,3,1,1,2
8,8,3,1,2,3
9,9,3,1,3,4
10,10,2,1,1,2
11,11,2,1,2,3
12,12,2,1,3,4
13,13,1,1,1,2
14,14,1,1,2,3
15,15,1,1,3,4
BRACE CONNECTIVITY
1,1,1,1,5,4,3,2,6708
2,1,1,1,4,3,2,3,6708
3,1,1,1,3,2,3,2,6708
4,1,1,1,2,1,2,3,6708
5,1,1,1,1,0,3,2,6708
ANALYSIS TYPE
3
STATIC ANALYSIS OPTION
0,0,0,0
DYNAMIC ANALYSIS CONTROL PARAMETER
0.35,0.0,0.005,64.996,5,3
INPUT WAVE
0,3251,0.02
STRONG   MOTION
coalinga.dat
SNAPSHOT CONTROL
0
0,0,0,0,0
OUTPUT CONTROL
5,0.02,1,2,3,4,5
LEVEL1.OUT
LEVEL2.OUT
LEVEL3.OUT
LEVEL4.OUT
LEVEL5.OUT
ELEMENT HYSTERESIS OUTPUT
1,1,0,0,0,0
COLUMN OUTPUT
1
BEAM OUTPUT
1
```

A.2 Output File

```
                    INELASTIC DAMAGE ANALYSIS OF REINFORCED CONCRETE STRUCTURES

                                   VERSION 4.0 (Beta Ver.)


                            STATE UNIVERSITY OF NEW YORK AT BUFFALO
                               DEPARTMENT OF CIVIL ENGINEERING

                                       APRIL 1995


INPUT DATA:

TITLE: DAMPER

********** CONTROL DATA **********

NUMBER OF STORIES ...........    5
NUMBER OF FRAMES ............    1

NO. OF TYPES OF CONCRETE .....   1
NO. OF TYPES OF STEEL ........   1

NO. OF TYPES OF MASONRY ......   0

P-DELTA EFFECTS ..............   1     ( = 0, IGNORE; = 1, INCLUDE )
COMPUTER PLATAFORM ...........   1     ( = 0, MAINFRAME; = 1, PC )

********** ELEMENT INFORMATION **********

NO. OF TYPES OF COLUMNS ...............   20
NO. OF TYPES OF BEAMS .................   15
NO. OF TYPES OF SHEAR WALLS ...........    0
NO. OF TYPES OF EDGE COLUMNS ..........    0
NO. OF TYPES OF TRANSVERSE BEAMS ......    0
NO. OF TYPES OF DISCRETE SPRINGS ......    0
NO. OF TYPES OF VISCOUS DAMPERS .......    1
NO. OF TYPES OF FRICTION DAMPERS ......    0
NO. OF TYPES OF HYSTERETIC DAMPERS ....    0
NO. OF TYPES OF INFILL PANELS .........    0

SYSTEM OF UNITS:  MM, kN

********** STORY HEIGHTS **********

STORY         HEIGHT
            FROM BASE

    5      15000.0000
    4      12000.0000
    3       9000.0000
    2       6000.0000
    1       3000.0000
```

********** WEIGHT DISTRIBUTION **********

STORY	FRAME	J-COORD. POSITION 1	2	3	4
1	1	110.00	110.00	110.00	110.00
2	1	110.00	110.00	110.00	110.00
3	1	110.00	110.00	110.00	110.00
4	1	110.00	110.00	110.00	110.00
5	1	110.00	110.00	110.00	110.00

ENVELOPE PROPERTIES: PROGRAM GENERATED
==

********** CONCRETE PROPERTIES **********

TYPE	UNCONF COMPRESS STRENGTH	INITIAL ELASTIC MODULUS	STRAIN AT MAX COMP STRENGTH	TENSILE STRENGTH
1	.028	24.87	.002000	.0033

ULTIMATE STRAIN	Z-FACTOR
.000000	.0000

(DEFAULT DATA FOR EPSU AND ZF IS GENERATED AT ELEMENT INPUT LEVEL)

********** REINFORCEMENT PROPERTIES **********

TYPE	YIELD STRENGTH	ULTIMATE STRENGTH	YOUNGS MODULUS	MODULUS AT HARDENING	STRAIN AT HARDENING (%)
1	.400	.560	199.949	1.356	3.000

********** PROPERTIES FOR HYSTERETIC RULE **********

NO. OF TYPES OF HYSTERETIC RULES: 2

RULE NO.	STIFFNESS DEGRADING FACTOR	STRENGTH DEGRADING FACTOR (DUCTILITY)	STRENGTH DEGRADING FACTOR (ENERGY)	TARGET SLIP FACTOR
1	2.000	.000	.100	1.000
2	2.000	.000	.100	1.000

COLUMN PROPERTIES: PROGRAM GENERATED
=====================================

********** COLUMN TYPES **********

COL. TYPE	SHAPE	CONC TYPE	STEEL TYPE	AXIAL LOAD	LENGTH	** RIGID ZONES ** (BOT)	(TOP)
1	RECT.	1	1	137.50	3000.00	200.00	200.00
2	RECT.	1	1	275.00	3000.00	200.00	200.00
3	RECT.	1	1	275.00	3000.00	200.00	200.00
4	RECT.	1	1	137.50	3000.00	200.00	200.00
5	RECT.	1	1	137.50	3000.00	200.00	200.00
6	RECT.	1	1	275.00	3000.00	200.00	200.00
7	RECT.	1	1	275.00	3000.00	200.00	200.00
8	RECT.	1	1	137.50	3000.00	200.00	200.00
9	RECT.	1	1	137.50	3000.00	225.00	225.00
10	RECT.	1	1	275.00	3000.00	225.00	225.00
11	RECT.	1	1	275.00	3000.00	225.00	225.00
12	RECT.	1	1	137.50	3000.00	225.00	225.00
13	RECT.	1	1	137.50	3000.00	225.00	225.00
14	RECT.	1	1	275.00	3000.00	225.00	225.00
15	RECT.	1	1	275.00	3000.00	225.00	225.00
16	RECT.	1	1	137.50	3000.00	225.00	225.00
17	RECT.	1	1	137.50	3000.00	225.00	225.00
18	RECT.	1	1	275.00	3000.00	225.00	225.00
19	RECT.	1	1	275.00	3000.00	225.00	225.00
20	RECT.	1	1	137.50	3000.00	225.00	225.00

CROSS SECTION DATA- RECTANGULAR COLUMNS:

TYPE	REGION	HYS RULE	DEPTH	WIDTH	COVER	REINF. AREA	HOOP BAR DIAMETER	HOOP BAR SPACING	CONFINEMENT EFFECTIVENESS
1	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
2	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
3	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
4	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
5	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
6	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500

7	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
8	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
9	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
10	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
11	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
12	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
13	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
14	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
15	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
16	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
17	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
18	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
19	TOP	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	2640.00	10.00	200.000	.500
20	TOP	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500
	BOT	1	400.00	400.00	40.00	1920.00	10.00	200.000	.500

BEAM PROPERTIES: PROGRAM GENERATED
===================================

********** BEAM TYPES **********

BEAM TYPE	CONC TYPE	STEEL TYPE	LENGTH	*** RIGID ZONES *** (LEFT)	(RIGHT)
1	1	1	6000.00	200.00	200.00
2	1	1	6000.00	200.00	200.00
3	1	1	6000.00	200.00	200.00
4	1	1	6000.00	200.00	200.00
5	1	1	6000.00	200.00	200.00
6	1	1	6000.00	200.00	200.00
7	1	1	6000.00	200.00	200.00
8	1	1	6000.00	200.00	200.00
9	1	1	6000.00	200.00	200.00
10	1	1	6000.00	200.00	200.00
11	1	1	6000.00	200.00	200.00
12	1	1	6000.00	200.00	200.00
13	1	1	6000.00	200.00	200.00
14	1	1	6000.00	200.00	200.00
15	1	1	6000.00	200.00	200.00

CROSS-SECTION DATA:

TYPE	SIDE	HYS RULE	DEPTH	WEB WIDTH	FLANGE WIDTH	SLAB DEPTH	COVER	** REINF. (BOT)
1	LEFT	2	400.00	300.00	300.00	.00	30.00	550.00
	RIGHT	2	400.00	300.00	300.00	.00	30.00	550.00
2	LEFT	2	400.00	300.00	300.00	.00	30.00	550.00
	RIGHT	2	400.00	300.00	300.00	.00	30.00	550.00
3	LEFT	2	400.00	300.00	300.00	.00	30.00	550.00
	RIGHT	2	400.00	300.00	300.00	.00	30.00	550.00
4	LEFT	2	400.00	300.00	300.00	.00	30.00	550.00
	RIGHT	2	400.00	300.00	300.00	.00	30.00	550.00

AREA ** (TOP)	STIRRUP DIA.	STIRRUP SPAC.
2200.00	10.00	230.00
2200.00	10.00	230.00
2200.00	10.00	230.00
2200.00	10.00	230.00
2200.00	10.00	230.00
2200.00	10.00	230.00
2200.00	10.00	230.00
2200.00	10.00	230.00

```
    5 LEFT       2    400.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    400.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    230.00
2200.00     10.00    230.00

    6 LEFT       2    400.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    400.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    230.00
2200.00     10.00    230.00

    7 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

    8 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

    9 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

   10 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

   11 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

   12 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

   13 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00

2200.00     10.00    250.00
2200.00     10.00    250.00

   14 LEFT       2    450.00   300.00   300.00       .00     30.00    550.00
      RIGHT      2    450.00   300.00   300.00       .00     30.00    550.00
```

2200.00	10.00	250.00					
2200.00	10.00	250.00					
15 LEFT	2	450.00	300.00	300.00	.00	30.00	550.00
RIGHT	2	450.00	300.00	300.00	.00	30.00	550.00
2200.00	10.00	250.00					
2200.00	10.00	250.00					

*************** NODAL CONNECTIVITY INFORMATION ***************

********** COLUMN ELEMENTS **********

COL. NO.	TYPE	FRAME #	COL LINE	STORY # (BOT)	STORY # (TOP)
1	1	1	1	4	5
2	2	1	2	4	5
3	3	1	3	4	5
4	4	1	4	4	5
5	5	1	1	3	4
6	6	1	2	3	4
7	7	1	3	3	4
8	8	1	4	3	4
9	9	1	1	2	3
10	10	1	2	2	3
11	11	1	3	2	3
12	12	1	4	2	3
13	13	1	1	1	2
14	14	1	2	1	2
15	15	1	3	1	2
16	16	1	4	1	2
17	17	1	1	0	1
18	18	1	2	0	1
19	19	1	3	0	1
20	20	1	4	0	1

********** BEAM ELEMENTS **********

BEAM NO.	TYPE	STORY #	FRAME #	COL LINE (LEFT)	COL LINE (RIGHT)
1	1	5	1	1	2
2	2	5	1	2	3
3	3	5	1	3	4
4	4	4	1	1	2
5	5	4	1	2	3
6	6	4	1	3	4
7	7	3	1	1	2
8	8	3	1	2	3
9	9	3	1	3	4
10	10	2	1	1	2
11	11	2	1	2	3
12	12	2	1	3	4
13	13	1	1	1	2

14	14	1	1	2	3
15	15	1	1	3	4

********** FRAME ELEVATION AND ELEMENT TYPES **********

ELEVATION OF FRAME NO. 1

```
+-----------+-----------+-----------+
!    001    !    002    !    003    !
!           !           !           !
! 001       ! 002       ! 003       ! 004
!           !           !           !
!           !           !           !
+-----------+-----------+-----------+
!    004    !    005    !    006    !
!           !           !           !
! 005       ! 006       ! 007       ! 008
!           !           !           !
!           !           !           !
+-----------+-----------+-----------+
!    007    !    008    !    009    !
!           !           !           !
! 009       ! 010       ! 011       ! 012
!           !           !           !
!           !           !           !
+-----------+-----------+-----------+
!    010    !    011    !    012    !
!           !           !           !
! 013       ! 014       ! 015       ! 016
!           !           !           !
!           !           !           !
+-----------+-----------+-----------+
!    013    !    014    !    015    !
!           !           !           !
! 017       ! 018       ! 019       ! 020
!           !           !           !
!           !           !           !
```

NOTATION:

```
-  =  BEAM              NUMBERS INDICATE ELEMENT TYPES
!  =  COLUMN            COLUMN TYPE NUMBERS ON RIGHT
W  =  SHEAR WALL        SHEAR WALL NUMBERS ON LEFT, AND
I  =  EDGE COLUMN       EDGE COLUMN NUMBERS BELOW COLUMN TYPES
```

********** COLUMN PROPERTIES **********

NO.	LENGTH	REGION	HYST RULE	RIGID ZONE	FLEXURAL STIFFNESS	AXIAL STIFFNESS
1	3000.0000	TOP	1	.2000E+03	.4867E+11	.1326E+04
		BOT	1	.2000E+03	.4867E+11	.1326E+04
2	3000.0000	TOP	1	.2000E+03	.6198E+11	.1326E+04
		BOT	1	.2000E+03	.6198E+11	.1326E+04
3	3000.0000	TOP	1	.2000E+03	.6198E+11	.1326E+04
		BOT	1	.2000E+03	.6198E+11	.1326E+04

4	3000.0000	TOP	1	.2000E+03	.4867E+11	.1326E+04
		BOT	1	.2000E+03	.4867E+11	.1326E+04
5	3000.0000	TOP	1	.2000E+03	.4867E+11	.1326E+04
		BOT	1	.2000E+03	.4867E+11	.1326E+04
6	3000.0000	TOP	1	.2000E+03	.6198E+11	.1326E+04
		BOT	1	.2000E+03	.6198E+11	.1326E+04
7	3000.0000	TOP	1	.2000E+03	.6198E+11	.1326E+04
		BOT	1	.2000E+03	.6198E+11	.1326E+04
8	3000.0000	TOP	1	.2000E+03	.4867E+11	.1326E+04
		BOT	1	.2000E+03	.4867E+11	.1326E+04
9	3000.0000	TOP	1	.2250E+03	.4867E+11	.1326E+04
		BOT	1	.2250E+03	.4867E+11	.1326E+04
10	3000.0000	TOP	1	.2250E+03	.6198E+11	.1326E+04
		BOT	1	.2250E+03	.6198E+11	.1326E+04
11	3000.0000	TOP	1	.2250E+03	.6198E+11	.1326E+04
		BOT	1	.2250E+03	.6198E+11	.1326E+04
12	3000.0000	TOP	1	.2250E+03	.4867E+11	.1326E+04
		BOT	1	.2250E+03	.4867E+11	.1326E+04
13	3000.0000	TOP	1	.2250E+03	.4867E+11	.1326E+04
		BOT	1	.2250E+03	.4867E+11	.1326E+04
14	3000.0000	TOP	1	.2250E+03	.6198E+11	.1326E+04
		BOT	1	.2250E+03	.6198E+11	.1326E+04
15	3000.0000	TOP	1	.2250E+03	.6198E+11	.1326E+04
		BOT	1	.2250E+03	.6198E+11	.1326E+04
16	3000.0000	TOP	1	.2250E+03	.4867E+11	.1326E+04
		BOT	1	.2250E+03	.4867E+11	.1326E+04
17	3000.0000	TOP	1	.2250E+03	.4867E+11	.1326E+04
		BOT	1	.2250E+03	.4867E+11	.1326E+04
18	3000.0000	TOP	1	.2250E+03	.6198E+11	.1326E+04
		BOT	1	.2250E+03	.6198E+11	.1326E+04
19	3000.0000	TOP	1	.2250E+03	.6198E+11	.1326E+04
		BOT	1	.2250E+03	.6198E+11	.1326E+04
20	3000.0000	TOP	1	.2250E+03	.4867E+11	.1326E+04
		BOT	1	.2250E+03	.4867E+11	.1326E+04

NO.	SECT	PCP	PYP	UYP	UUP	EI3P	PCN	PYN	UYN	UUN	EI3N
1	TOP	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09
	BOT	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09
2	TOP	.2066E+06	.3756E+06	.1083E-04	.2916E-03	.3220E+09	-.2066E+06	-.3756E+06	-.1083E-04	-.2916E-03	.3220E+09
	BOT	.2066E+06	.3756E+06	.1083E-04	.2916E-03	.3220E+09	-.2066E+06	-.3756E+06	-.1083E-04	-.2916E-03	.3220E+09
3	TOP	.2066E+06	.3756E+06	.1083E-04	.2916E-03	.3220E+09	-.2066E+06	-.3756E+06	-.1083E-04	-.2916E-03	.3220E+09
	BOT	.2066E+06	.3756E+06	.1083E-04	.2916E-03	.3220E+09	-.2066E+06	-.3756E+06	-.1083E-04	-.2916E-03	.3220E+09
4	TOP	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09
	BOT	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09
5	TOP	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09
	BOT	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09					

```
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
    6   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
    7   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
    8   TOP   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
        BOT   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
    9   TOP   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
        BOT   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
   10   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
   11   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
   12   TOP   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
        BOT   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
   13   TOP   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
        BOT   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
   14   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
   15   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
   16   TOP   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
        BOT   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
   17   TOP   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
        BOT   .1477E+06   .2686E+06   .1158E-04   .3617E-03   .2297E+09
-.1477E+06  -.2686E+06  -.1158E-04  -.3617E-03   .2297E+09
   18   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
   19   TOP   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
        BOT   .2066E+06   .3756E+06   .1083E-04   .2916E-03   .3220E+09
-.2066E+06  -.3756E+06  -.1083E-04  -.2916E-03   .3220E+09
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20	TOP	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09
	BOT	.1477E+06	.2686E+06	.1158E-04	.3617E-03	.2297E+09	-.1477E+06	-.2686E+06	-.1158E-04	-.3617E-03	.2297E+09

********** BEAM PROPERTIES **********

NO.	LENGTH	REGION	HYST RULE	RIGID ZONE	FLEXURAL STIFFNESS
1	6000.0000	LEFT	2	.2000E+03	.3146E+11
		RGHT	2	.2000E+03	.3146E+11
2	6000.0000	LEFT	2	.2000E+03	.3146E+11
		RGHT	2	.2000E+03	.3146E+11
3	6000.0000	LEFT	2	.2000E+03	.3146E+11
		RGHT	2	.2000E+03	.3146E+11
4	6000.0000	LEFT	2	.2000E+03	.3146E+11
		RGHT	2	.2000E+03	.3146E+11
5	6000.0000	LEFT	2	.2000E+03	.3146E+11
		RGHT	2	.2000E+03	.3146E+11
6	6000.0000	LEFT	2	.2000E+03	.3146E+11
		RGHT	2	.2000E+03	.3146E+11
7	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
8	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
9	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
10	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
11	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
12	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
13	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
14	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11
15	6000.0000	LEFT	2	.2000E+03	.4396E+11
		RGHT	2	.2000E+03	.4396E+11

NO.	SECT	PCP	PYP	UYP	UUP	EI3P	PCN	PYN	UYN	UUN	EI3N
1	LEFT	.4174E+05	.7588E+05	.7286E-05	.2331E-03	.7254E+08	-.1540E+06	-.2801E+06	-.1034E-04	-.8273E-04	.5364E+09
	RGHT	.4174E+05	.7588E+05	.7286E-05	.2331E-03	.7254E+08	-.1540E+06	-.2801E+06	-.1034E-04	-.8273E-04	.5364E+09
2	LEFT	.4174E+05	.7588E+05	.7286E-05	.2331E-03	.7254E+08	-.1540E+06	-.2801E+06	-.1034E-04	-.8273E-04	.5364E+09
	RGHT	.4174E+05	.7588E+05	.7286E-05	.2331E-03	.7254E+08	-.1540E+06	-.2801E+06	-.1034E-04	-.8273E-04	.5364E+09
3	LEFT	.4174E+05	.7588E+05	.7286E-05	.2331E-03	.7254E+08	-.1540E+06	-.2801E+06	-.1034E-04	-.8273E-04	.5364E+09
	RGHT	.4174E+05	.7588E+05	.7286E-05	.2331E-03	.7254E+08					

```
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
    4  LEFT   .4174E+05   .7588E+05   .7286E-05   .2331E-03   .7254E+08
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
       RGHT   .4174E+05   .7588E+05   .7286E-05   .2331E-03   .7254E+08
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
    5  LEFT   .4174E+05   .7588E+05   .7286E-05   .2331E-03   .7254E+08
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
       RGHT   .4174E+05   .7588E+05   .7286E-05   .2331E-03   .7254E+08
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
    6  LEFT   .4174E+05   .7588E+05   .7286E-05   .2331E-03   .7254E+08
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
       RGHT   .4174E+05   .7588E+05   .7286E-05   .2331E-03   .7254E+08
-.1540E+06  -.2801E+06  -.1034E-04  -.8273E-04   .5364E+09
    7  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
    8  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
    9  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
   10  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
   11  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
   12  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
   13  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
   14  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
   15  LEFT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09
       RGHT   .4781E+05   .8693E+05   .6437E-05   .2060E-03   .9879E+08
-.1810E+06  -.3291E+06  -.1458E-04  -.1166E-03   .5360E+09

 **************************************** D Y N A M I C   A N A L Y S I S
****************************************

 INPUT DATA:

 ********** DETAILS OF INPUT BASE MOTION **********
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MAX SCALED VALUE OF HORIZONTAL COMPONENT (g): .350

MAX SCALED VALUE OF VERTICAL COMPONENT (g): .000

TIME INTERVAL OF ANALYSIS (SEC): .0050

TOTAL DURATION OF RESPONSE ANALYSIS (SEC): 64.996

DAMPING COEFFICIENT (% OF CRITICAL): 5.000

DAMPING TYPE: RAYLEIGH DAMPING

VERTICAL COMPONENT OF BASE MOTION: 0

(=0, NOT INCLUDED; =1, INCLUDED)

WAVE NAME: STRONG MOTION

NO. OF POINTS IN INPUT BASE MOTION: 3251

TIME INTERVAL OF INPUT WAVE (SEC): .020

********** OUTPUT CONTROL DATA **********
NO. OF STORIES FOR WHICH OUTPUT IS REQUIRED: 5

NO.	STORY NUMBER
1	1
2	2
3	3
4	4
5	5

******************************** MODAL ANALYSIS ******************************

MODE	FREQUENCY(Hz)	PERIOD(SEC)	MODAL PARTICIPATION FACTOR	MODAL WEIGHT (WEIGHT UNITS)	RELATIVE MODAL WEIGHT (%)
1	1.28	.78	.4250	69.746	3.170
2	3.99	.25	.1595	9.819	.446
3	7.78	.13	.1042	4.197	.191
4	12.47	.08	.0728	2.046	.093
5	16.99	.06	.0456	.801	.036

TOTAL WEIGHT... 2200.000

******************** EIGEN VECTORS (MAXIMUM NORMALIZED) ********************

STORY	1	2	3	4	5
5	1.000	-.992	.789	-.410	.176
4	.862	-.044	-.932	.960	-.550
3	.659	.815	-.749	-.663	.881
2	.415	1.000	.847	-.329	-1.000
1	.156	.505	1.000	1.000	.856

********************* EIGEN VECTORS (MASS NORMALIZED) **********************

STORY	1	2	3	4	5
5	3.065	-2.748	1.919	-1.192	.492
4	2.642	-.122	-2.266	2.792	-1.541
3	2.019	2.257	-1.822	-1.928	2.467
2	1.272	2.771	2.061	-.955	-2.801
1	.477	1.398	2.432	2.907	2.398

**************** END OF MODAL ANALYSIS ****************

SEQUENCE OF COMPONENT CRACKING/YIELDING

CURRENT TIME: 2.9550

BEAM 10: CRACK INITIATED AT LEFT
BEAM 13: CRACK INITIATED AT LEFT

CURRENT TIME: 2.9600

BEAM 12: CRACK INITIATED AT LEFT
BEAM 15: CRACK INITIATED AT LEFT

CURRENT TIME: 2.9650

BEAM 11: CRACK INITIATED AT LEFT

CURRENT TIME: 2.9750

BEAM 14: CRACK INITIATED AT LEFT

CURRENT TIME: 3.0200

BEAM 7: CRACK INITIATED AT LEFT

CURRENT TIME: 3.0450

BEAM 9: CRACK INITIATED AT LEFT

CURRENT TIME: 3.2500

BEAM 13: CRACK INITIATED AT RGHT
BEAM 15: CRACK INITIATED AT RGHT

CURRENT TIME: 3.2550

BEAM 14: CRACK INITIATED AT RGHT

CURRENT TIME: 3.2650

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BEAM  12: CRACK INITIATED AT RGHT

CURRENT TIME:                 3.2700

BEAM  10: CRACK INITIATED AT RGHT
BEAM  11: CRACK INITIATED AT RGHT

CURRENT TIME:                 3.2900

BEAM   9: CRACK INITIATED AT RGHT

CURRENT TIME:                 3.2950

BEAM   7: CRACK INITIATED AT RGHT
BEAM   8: CRACK INITIATED AT RGHT

CURRENT TIME:                 3.3150

BEAM  15: YIELDING DETECTED AT RGHT

CURRENT TIME:                 3.3200

BEAM  13: YIELDING DETECTED AT RGHT

CURRENT TIME:                 3.3250

BEAM   5: CRACK INITIATED AT RGHT
BEAM   6: CRACK INITIATED AT RGHT
BEAM  12: YIELDING DETECTED AT RGHT
BEAM  14: YIELDING DETECTED AT RGHT

CURRENT TIME:                 3.3300

BEAM   4: CRACK INITIATED AT RGHT
BEAM  10: YIELDING DETECTED AT RGHT
BEAM  11: YIELDING DETECTED AT RGHT

CURRENT TIME:                 3.3450

COLUMN  17: CRACK INITIATED AT BOT

CURRENT TIME:                 3.3600

BEAM   9: YIELDING DETECTED AT RGHT

CURRENT TIME:                 3.3650

BEAM   7: YIELDING DETECTED AT RGHT
BEAM   8: YIELDING DETECTED AT RGHT

CURRENT TIME:                 3.4000

BEAM   3: CRACK INITIATED AT RGHT

CURRENT TIME:                 3.4150
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BEAM    1: CRACK INITIATED AT RGHT
BEAM    2: CRACK INITIATED AT RGHT

CURRENT TIME:                  3.6250

BEAM    8: CRACK INITIATED AT LEFT

CURRENT TIME:                  3.6400

BEAM    4: CRACK INITIATED AT LEFT
BEAM    5: CRACK INITIATED AT LEFT
BEAM    6: CRACK INITIATED AT LEFT

CURRENT TIME:                  3.6650

BEAM   10: YIELDING DETECTED AT LEFT
BEAM   11: YIELDING DETECTED AT LEFT
BEAM   12: YIELDING DETECTED AT LEFT

CURRENT TIME:                  3.6700

BEAM   13: YIELDING DETECTED AT LEFT

CURRENT TIME:                  3.6750

BEAM   14: YIELDING DETECTED AT LEFT
BEAM   15: YIELDING DETECTED AT LEFT

CURRENT TIME:                  3.6850

COLUMN   19: CRACK INITIATED AT BOT
COLUMN   20: CRACK INITIATED AT BOT
BEAM    7: YIELDING DETECTED AT LEFT

CURRENT TIME:                  3.6900

COLUMN   18: CRACK INITIATED AT BOT
BEAM    8: YIELDING DETECTED AT LEFT
BEAM    9: YIELDING DETECTED AT LEFT

CURRENT TIME:                  3.7800

BEAM    1: CRACK INITIATED AT LEFT

CURRENT TIME:                  3.7850

BEAM    3: CRACK INITIATED AT LEFT

CURRENT TIME:                  3.7900

BEAM    2: CRACK INITIATED AT LEFT
BEAM    4: YIELDING DETECTED AT LEFT

CURRENT TIME:                  3.7950

BEAM    5: YIELDING DETECTED AT LEFT
BEAM    6: YIELDING DETECTED AT LEFT
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```
CURRENT TIME:                    4.6850

BEAM    5: YIELDING DETECTED AT RGHT

CURRENT TIME:                    4.6900

BEAM    4: YIELDING DETECTED AT RGHT
BEAM    6: YIELDING DETECTED AT RGHT

CURRENT TIME:                    4.7350

COLUMN  18: YIELDING DETECTED AT BOT

CURRENT TIME:                    4.7400

COLUMN  19: YIELDING DETECTED AT BOT

CURRENT TIME:                    4.7800

COLUMN  20: YIELDING DETECTED AT BOT

CURRENT TIME:                    4.7900

COLUMN  11: CRACK INITIATED AT TOP

CURRENT TIME:                    4.8300

COLUMN  15: CRACK INITIATED AT BOT

CURRENT TIME:                    4.8350

COLUMN  14: CRACK INITIATED AT BOT

CURRENT TIME:                    4.8450

BEAM    3: YIELDING DETECTED AT RGHT

CURRENT TIME:                    4.8550

COLUMN  13: CRACK INITIATED AT BOT
BEAM    1: YIELDING DETECTED AT RGHT

CURRENT TIME:                    4.8600

COLUMN   7: CRACK INITIATED AT TOP
COLUMN   8: CRACK INITIATED AT TOP
BEAM    2: YIELDING DETECTED AT RGHT

CURRENT TIME:                    4.8650

COLUMN   6: CRACK INITIATED AT TOP
COLUMN  16: CRACK INITIATED AT BOT

CURRENT TIME:                    4.8750

COLUMN   5: CRACK INITIATED AT TOP
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CURRENT TIME:                    5.2750

BEAM    1: YIELDING DETECTED AT LEFT

CURRENT TIME:                    5.2800

BEAM    3: YIELDING DETECTED AT LEFT

CURRENT TIME:                    5.2850

BEAM    2: YIELDING DETECTED AT LEFT

CURRENT TIME:                    6.1800

COLUMN  17: YIELDING DETECTED AT BOT

       ********** MAXIMUM RESPONSE **********

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----------------
 STORY    STORY SHEAR    DRIFT RATIO(%)    STORY DRIFT    DISPLACEMENT

VELOCITY    ACCELERATION    STORY VELOCITY DRIFT
 -------------------------------------------------------------------------------
----------------

    5       211.40          1.38           41.3307        206.7509
991.0794    4422.2989      234.5140
    4       281.79          1.61           48.2824        168.7446
877.7037    3334.7789      222.3392
    3       355.48          1.75           52.4647        120.4933
668.7054    3106.7220      296.0404
    2       408.13          1.52           45.4550         70.3529
373.6153    3584.4189      261.6561
    1       458.01           .87           25.9575         25.9575
130.8268    3153.7440      130.8268


         ********** MAXIMUM FORCES **********
                  (TIME AT MAXIMUM)


 *** COLUMNS ***

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 NO.              MOMENT      MOMENT       SHEAR       SHEAR       AXIAL
                    (+)         (-)         (+)         (-)       (TENS)
AXIAL          MOMENT DEMAND/CAPACITY
 (COMP)          (+)          (-)
--------------------------------------------------------------------------------
------------------------------

   1   BOT     .7264E+05  -.6401E+05   .3629E+02  -.3610E+02   .0000E+00
                (   6.28)   (   5.34)   (  10.54)   (   4.96)   (     .00)
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```
-.1739E+03        .270          .238
(4.96)
       TOP    .1237E+06  -.8538E+05
(   4.95)   (   5.47)
              .461          .318

   2   BOT    .6093E+05  -.5341E+05   .6564E+02  -.7319E+02   .0000E+00
            (   5.04)   (   5.33)   (   5.46)   (   4.96)   (    .00)
-.2757E+03        .162          .142
 (3.96)
       TOP    .1991E+06  -.1816E+06
            (   4.95)   (   5.47)
              .530          .483

   3   BOT    .6089E+05  -.5352E+05   .6560E+02  -.7369E+02   .0000E+00
(   5.04)   (   5.33)   (   5.46)   (   6.38)   (    .00)
-.2768E+03        .162          .142
 (   5.82)
       TOP    .1976E+06  -.1817E+06
            (   4.95)   (   5.47)
              .526          .484

   4   BOT    .7498E+05  -.7037E+05   .2476E+02  -.3333E+02   .0000E+00
(   4.88)   (   5.33)   (   3.95)   (   8.55)   (    .00)
-.1692E+03        .279          .262
 (   5.47)
       TOP    .8445E+05  -.9729E+05
            (   4.92)   (   5.47)
              .314          .362

   5   BOT    .8019E+05  -.5651E+05   .5011E+02  -.5264E+02   .0000E+00
(  10.55)   (   8.55)   (   5.48)   (   4.91)   (    .00)
-.2058E+03        .299          .210
 (   4.94)
       TOP    .1488E+06  -.1428E+06
            (   4.88)   (   5.34)
              .554          .532

   6   BOT    .1007E+06  -.9892E+05   .8198E+02  -.8584E+02   .0000E+00
(  10.54)   (   8.55)   (   5.48)   (   4.91)   (    .00)
-.2786E+03        .268          .263

 (  14.06)
       TOP    .2106E+06  -.1977E+06
            (   4.88)   (   5.34)
              .561          .526

   7   BOT    .9885E+05  -.1003E+06   .8020E+02  -.8749E+02   .0000E+00
(  10.54)   (   8.55)   (   3.92)   (   4.91)   (    .00)
-.2770E+03        .263          .267
 (   5.83)
       TOP    .2123E+06  -.1958E+06
            (   4.88)   (   5.34)
.565        .521

   8   BOT    .6233E+05  -.7639E+05   .4912E+02  -.5253E+02   .0000E+00
(   6.18)   (   8.55)   (   3.92)   (   4.92)   (    .00)
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```
-.1997E+03         .232           .284
 (    5.47)
        TOP     .1514E+06  -.1374E+06
                 (    4.88)   (    5.34)
.564            .512

   9   BOT     .9601E+05  -.7404E+05   .6886E+02  -.6461E+02   .0000E+00
(  10.54)   (    3.45)   (    5.34)   (    4.88)   (     .00)
-.2401E+03         .357           .276
 (    4.92)
        TOP     .1335E+06  -.1113E+06

                 (    4.80)   (    5.31)
.497            .415

  10   BOT     .1256E+06  -.1164E+06   .1061E+03  -.1106E+03   .0000E+00
(    5.50)   (    3.44)   (    5.35)   (    4.88)   (     .00)
-.2791E+03         .334           .310
 (  14.07)
        TOP     .2058E+06  -.1805E+06
                 (    4.80)   (    3.85)
.548            .480

  11   BOT     .1254E+06  -.1153E+06   .1050E+03  -.1113E+03   .0000E+00
(    5.50)   (    3.44)   (    5.35)   (    4.88)   (     .00)
-.2776E+03         .334           .307
 (    5.81)
        TOP     .2074E+06  -.1787E+06
                 (    4.80)   (    3.85)
.552            .476

  12   BOT     .7346E+05  -.9135E+05   .6041E+02  -.6211E+02   .0000E+00
(    5.50)   (    8.57)   (    3.88)   (    6.27)   (     .00)
-.2333E+03         .274           .340
 (    5.47)
        TOP     .1404E+06  -.1140E+06
                 (    6.19)   (    3.85)
.523            .424

  13   BOT     .1731E+06  -.1480E+06   .7136E+02  -.7956E+02   .0000E+00
(    5.36)   (    4.86)   (    5.30)   (    4.83)   (     .00)
-.2725E+03         .644           .551
 (    4.87)
        TOP     .7796E+05  -.6532E+05
                 (    6.16)   (    8.57)
.290            .243

  14   BOT     .2547E+06  -.2115E+06   .1193E+03  -.1221E+03   .0000E+00
(    5.48)   (    4.86)   (    3.84)   (    4.83)   (     .00)
-.2792E+03         .678           .563
 (  14.07)
        TOP     .1305E+06  -.1104E+06
                 (    6.16)   (    3.80)
.347            .294

  15   BOT     .2517E+06  -.2142E+06   .1204E+03  -.1237E+03   .0000E+00
(    5.36)   (    4.86)   (    3.84)   (    4.82)   (     .00)
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```
-.2778E+03        .670          .570
 (    5.80)
       TOP     .1320E+06   -.1105E+06
               (    6.16)   (    3.80)
.351           .294
  16   BOT     .1633E+06   -.1482E+06    .7410E+02   -.8031E+02    .0000E+00
(    5.36)   (    4.87)   (    3.84)   (    6.22)   (      .00)
-.2677E+03        .608          .552
 (    3.89)
       TOP     .9709E+05   -.6125E+05
               (    8.33)   (    3.80)
.362           .228

  17   BOT     .2463E+06   -.2687E+06    .7173E+02   -.8628E+02    .3179E+02
(    5.44)   (    6.18)   (    3.80)   (    6.16)   (    3.87)
-.3033E+03        .917         1.000
 (    3.42)
       TOP     .9725E+05   -.1151E+06
               (    5.36)   (    4.93)
.362           .429
  18   BOT     .3769E+06   -.3757E+06    .1223E+03   -.1410E+03    .0000E+00
(    5.44)   (    4.80)   (    3.81)   (    4.73)   (      .00)
-.2792E+03       1.004         1.000
 (   14.07)
       TOP     .1459E+06   -.1187E+06
               (    5.65)   (    4.94)
.388           .316

  19   BOT     .3768E+06   -.3757E+06    .1247E+03   -.1414E+03    .0000E+00
(    5.44)   (    4.78)   (    3.81)   (    4.73)   (      .00)
-.2802E+03       1.003         1.000
 (    4.04)
       TOP     .1441E+06   -.1183E+06
               (    5.65)   (    4.94)
                  .384          .315

  20   BOT     .2496E+06   -.2686E+06    .7823E+02   -.9256E+02    .3043E+02
(    5.44)   (    4.78)   (    3.81)   (    6.16)   (    4.85)
-.3040E+03        .929         1.000
 (    3.87)
       TOP     .1138E+06   -.9783E+05
               (    5.65)   (    4.93)
                  .424          .364
```

*** BEAMS ***

NO.		MOMENT (+)	MOMENT (-)	SHEAR (+)	SHEAR (-)	DEMAND/CAPACITY MOMENT (+)	DEMAND/CAPACITY (-)
1	LEFT	.8053E+05	-.1232E+06	.3226E+02	-.3595E+02	1.061	.440
		(5.47)	(4.95)				
	RGHT	.8038E+05	-.1001E+06			1.059	.358
		(6.38)	(5.47)				
2	LEFT	.8027E+05	-.1195E+06	.3232E+02	-.3528E+02	1.058	.427
		(5.47)	(4.95)				
	RGHT	.8043E+05	-.1007E+06			1.060	.360
		(6.38)	(5.47)				
3	LEFT	.8006E+05	-.1181E+06	.3147E+02	-.3509E+02	1.055	.422
		(5.47)	(4.95)				
	RGHT	.8059E+05	-.9618E+05			1.062	.343
		(6.38)	(5.47)				
4	LEFT	.8157E+05	-.9608E+05	.3456E+02	-.3143E+02	1.075	.343
		(5.47)	(4.94)				
	RGHT	.8113E+05	-.1156E+06			1.069	.413
		(6.38)	(3.93)				
5	LEFT	.8161E+05	-.9677E+05	.3438E+02	-.3158E+02	1.075	.346
		(5.47)	(4.94)				
	RGHT	.8129E+05	-.1147E+06			1.071	.409
		(6.38)	(3.93)				
6	LEFT	.8159E+05	-.9811E+05	.3440E+02	-.3182E+02	1.075	.350
		(5.47)	(4.94)				
	RGHT	.8129E+05	-.1148E+06			1.071	.410
		(6.38)	(3.93)				
7	LEFT	.9475E+05	-.1401E+06	.3815E+02	-.4092E+02	1.090	.426
		(5.49)	(3.44)				
	RGHT	.9441E+05	-.1217E+06			1.086	.370
		(6.32)	(3.90)				

```
  8  LEFT    .9467E+05  -.1361E+06   .3762E+02  -.4021E+02          1.089
              (   5.49)   (   3.44)
.414
     RGHT    .9479E+05  -.1190E+06                                  1.090
              (   6.32)   (   3.90)
.362
  9  LEFT    .9431E+05  -.1343E+06   .3715E+02  -.3994E+02          1.085
              (   5.49)   (   3.44)
.408
     RGHT    .9453E+05  -.1166E+06                                  1.087
              (   6.32)   (   3.90)
.354
 10  LEFT    .9475E+05  -.1488E+06   .3779E+02  -.4260E+02          1.090
              (   5.48)   (   3.42)
.452
     RGHT    .9483E+05  -.1187E+06                                  1.091
              (   6.27)   (   3.87)
.361
 11  LEFT    .9478E+05  -.1462E+06   .3746E+02  -.4215E+02          1.090
              (   5.48)   (   3.42)
.444
     RGHT    .9491E+05  -.1169E+06                                  1.092
              (   6.27)   (   3.87)
.355
 12  LEFT    .9453E+05  -.1435E+06   .3656E+02  -.4171E+02          1.087
              (   5.48)   (   3.42)
.436
     RGHT    .9498E+05  -.1122E+06                                  1.093
              (   6.27)   (   3.87)
.341
 13  LEFT    .9338E+05  -.1288E+06   .3976E+02  -.3877E+02          1.074
              (   5.45)   (   3.39)
.391
     RGHT    .9416E+05  -.1306E+06                                  1.083
              (   6.22)   (   3.84)
.397
 14  LEFT    .9324E+05  -.1263E+06   .4100E+02  -.3831E+02          1.073
              (   5.45)   (   3.39)
.384
     RGHT    .9408E+05  -.1376E+06                                  1.082
              (   4.82)   (   3.84)
.418
 15  LEFT    .9302E+05  -.1237E+06   .3908E+02  -.3790E+02          1.070
              (   5.45)   (   3.39)
.376
     RGHT    .9448E+05  -.1272E+06                                  1.087
              (   4.82)   (   3.84)
.387
```

```
******************** D A M A G E D   S T A T E   O F   F R A M E S
********************
```

FINAL STATE OF FRAME NO. 1

```
+O---------O+O---------O+O---------O+
!           !           !           !
!           !           !           !
!           !           !           !
!           !           !           !
!           !           !           !
+O---------O+O---------O+O---------O+
x           x           x           x
!           !           !           !
!           !           !           !
!           !           !           !
!           !           !           !
+O---------O+O---------O+O---------O+
!           !           x           !
!           !           !           !
!           !           !           !
!           !           !           !
!           !           !           !
+O---------O+O---------O+O---------O+
!           !           !           !
!           !           !           !
!           !           !           !
!           !           !           !
x           x           x           x
+O---------O+O---------O+O---------O+
!           !           !           !
!           !           !           !
!           !           !           !
!           !           !           !
O           O           O           O
```

NOTATION:

```
-  =  BEAM
!  =  COLUMN                x  =  CRACK
W  =  SHEAR WALL            O  =  YIELD
I  =  EDGE COLUMN           FOR EDGE COLS: C: COMPRESSION
                                           T: TENSION
                                           O: TENSILE YIELD
```

```
************ DAMAGE ANALYSIS *************
****** MODIFIED PARK-ANG-WEN MODEL *******

********** DAMAGE DATA: COLUMNS
           ====================
```

NO.	*DEFORMATION* BOT	*DEFORMATION* TOP	***STRENGTH*** BOT	***STRENGTH*** TOP	HYST. ENERGY	TOTAL DAMAGE
1	.000	.000	.000	.000	.9061E-02	.000

2	.000	.000	.000	.000	.3220E-02	.000
3	.000	.000	.000	.000	.1927E-02	.000
4	.000	.000	.000	.000	.5275E-02	.000
5	.000	.056	.000	.000	.3246E+01	.055
6	.000	.069	.000	.000	.1979E+01	.068
7	.000	.069	.000	.000	.1908E+01	.068
8	.000	.056	.000	.000	.1011E-01	.056
9	.000	.000	.000	.000	.3450E-01	.000
10	.000	.000	.000	.000	.1495E-01	.000
11	.000	.051	.000	.000	.8474E-01	.042
12	.000	.000	.000	.000	.0000E+00	.000
13	.049	.000	.002	.000	.1625E+04	.052
14	.064	.000	.003	.000	.2663E+04	.067
15	.063	.000	.003	.000	.2644E+04	.066
16	.050	.000	.002	.000	.1521E+04	.052
17	.099	.000	.011	.000	.7862E+04	.110
18	.135	.000	.013	.000	.1087E+05	.149
19	.134	.000	.013	.000	.1064E+05	.147
20	.110	.000	.011	.000	.7953E+04	.121

********** DAMAGE DATA: BEAMS
==================

NO.	**DEFORMATION**		***STRENGTH***		HYST.	TOTAL
	LEFT	RIGHT	LEFT	RIGHT	ENERGY	DAMAGE
1	.123	.100	.020	.018	.1007E+05	.131
2	.118	.102	.019	.018	.9782E+04	.128
3	.116	.106	.020	.018	.1011E+05	.131
4	.139	.137	.026	.025	.1353E+05	.164
5	.138	.137	.026	.024	.1339E+05	.163
6	.138	.137	.027	.024	.1350E+05	.163
7	.133	.142	.035	.034	.1868E+05	.172
8	.131	.143	.033	.033	.1783E+05	.170
9	.130	.145	.036	.034	.1881E+05	.172
10	.135	.143	.033	.031	.1722E+05	.171
11	.133	.143	.033	.030	.1685E+05	.169
12	.133	.143	.033	.030	.1708E+05	.170
13	.116	.102	.024	.024	.1302E+05	.133
14	.116	.104	.024	.024	.1297E+05	.134
15	.114	.108	.025	.025	.1324E+05	.136

********** RESULTS OF DAMAGE ANALYSIS **********

DAMAGE INDEX STATISTICS OF FRAME NO. 1

```
+-----------+-----------+-----------+
!   0.13    !   0.13    !   0.13    !
!  (0.34)   !  (0.33)   !  (0.34)   !
!0.00       !0.00       !0.00       !0.00
!(.00)      !(.00)      !(.00)      !(.00)
!           !           !           !
+-----------+-----------+-----------+
!   0.16    !   0.16    !   0.16    !
!  (0.33)   !  (0.33)   !  (0.33)   !
!0.06       !0.07       !0.07       !0.06
!(.00)      !(.00)      !(.00)      !(.00)
!           !           !           !
+-----------+-----------+-----------+
!   0.17    !   0.17    !   0.17    !
!  (0.34)   !  (0.32)   !  (0.34)   !
!0.00       !0.00       !0.04       !0.00
!(.00)      !(.00)      !(.00)      !(.00)
!           !           !           !
+-----------+-----------+-----------+
!   0.17    !   0.17    !   0.17    !
!  (0.29)   !  (0.28)   !  (0.29)   !
!0.05       !0.07       !0.07       !0.05
!(.03)      !(.04)      !(.04)      !(.03)
!           !           !           !
+-----------+-----------+-----------+
!   0.13    !   0.13    !   0.14    !
!  (0.17)   !  (0.17)   !  (0.17)   !
!0.11       !0.15       !0.15       !0.12
!(.10)      !(.14)      !(.14)      !(.10)
!           !           !           !
```

********* STORY LEVEL DAMAGE INDICES **********

STORY	BEAM-SLAB DAMAGE	COL-WALL DAMAGE	WEIGHTING FACTOR
5	.130	.000	.114
4	.163	.000	.154
3	.172	.000	.211
2	.146	.009	.228
1	.069	.065	.292

OVERALL STRUCTURAL DAMAGE :   .151